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Study of the Solar Cycle From Space

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June 14-15, 1979

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Preface

The development of new observational and theoretical tools to probe the solar interior, as well as recent new data on the nature of the solar cycle, have led to the recognition of the opportunity for a significant advance in our understanding of the dynamics of the solar cycle, through a well-planned program of space observations over the coming decade.

In response to this opportunity, the National Aeronautics and Space Administration (NASA) has formed a Study Group to consider a possible program of solar cycle research known as the Solar Cycle and Dynamics Mission (SCADM). The Study Group, as part of its activities, organized a two-day Symposium, in order to marshal the best scientific imagination and wisdom of the astronomical and geophysical communities at an early stage in the program definition. Because of the obvious implications of such a program for astrophysics in general, the American Astronomical Society (AAS) agreed to co-sponsor this Symposium with NASA.

The present document contains the presentations and discussions from the Symposium, which was held on June 14-15, 1979, in Wellesley, Massachusetts. Most of the manuscripts have been reproduced exactly as submitted to expedite publication.

In addition to the papers actually presented at the Symposium, several related contributions have been included. The two introductory papers were prepared at the direction of the SCADM Study Group, and summarize the principle areas of research to emerge from that committee's deliberations. Appendix A contains papers that were accepted for the Symposium, but which could not be presented at the time. Finally, Appendix B contains the abstracts of papers which were given at a related special session of the Solar Physics Division of the AAS, also held at Wellesley, on the topic of Solar and Stellar Variability.

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Symposium on the Study of the Solar Cycle from Space
Wellesley, Massachusetts
14-15 June 1979

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1430 - 1515	T. Brown—The Opportunities Offered by SCADM for the Study of Surface Phenomena Related to Interior Structure and Dynamics
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	B. J. Rickett and W. A. Coles—Solar Cycle Changes in the High Latitude Solar Wind
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Symposium Organizing Committee

G. Newkirk, Chairman
J. Harvey
P. Gilman
R. J. Thomas

BACKGROUND PAPERS

DYNAMICS OF THE SOLAR INTERIOR AND THE SOLAR DYNAMO

Background paper for symposium on the Solar Cycle and Dynamics Mission

by Peter A. Gilman, HAO

N80-17945

I. Introduction and Goals

The solar convection zone is the origin of most of the variations in solar output observed or suspected to occur. The sun's magnetic field is rooted there, and solar activity and the solar cycle are generated and maintained there. Changes in the magnetic fields which reach into the solar atmosphere and beyond to interplanetary space are largely determined by the dynamo action of velocity fields in the convection zone. If changes in solar luminosity occur on time scales of months to millenia, such changes probably have their origin in the changing dynamics of the convection zone, either as cause of or in response to long term changes in the level of solar activity. Fluctuations would occur in the rate at which energy is brought to the surface by convection, and the solar diameter would be slightly modified.

To describe and ultimately understand the global workings of the solar dynamo requires simultaneous high quality photospheric observations of solar velocities, magnetic fields, intensity patterns, luminosity and various radiative outputs. The observations must be nearly continuous in time and of long duration--most or all of a solar cycle. Such a measurement program should be a major part of the proposed Solar Cycle and Dynamics Mission. It would be more ambitious than ever attempted before, but the potential now exists to make it successful.

Now is a particularly appropriate time to develop such a measurement program, for at least two reasons. First, recent evidence for a solar signal in terrestrial proxy records such as carbon 14 in tree rings, together with more sensitive dating techniques being developed, indicate we may soon be able to reconstruct solar history over the past several thousand years in some detail. We need a more detailed template of actual solar observations from which to extrapolate back. Second, theoretical and computational tools and models have now reached the point that quantitative modeling of the global circulation of the sun and its dynamo action is within reach, so that much better information than now exists on global solar velocities, magnetic field and intensity patterns is needed for comparisons with such models.

Beyond answering important questions concerning the solar dynamo itself, which we discuss in detail below, such an observing program offers a unique opportunity for insights into the behavior of dynamos occuring anywhere in the universe. The solar dynamo is the only one which offers the prospect of observing directly some of the primary motions responsible for the induction of magnetic fields. This is not possible for the planetary interiors or other stars.

II. Solar Questions to Answer

There are many aspects of the global behavior of the sun which we need to observe in detail before we can really understand the solar dynamo. Central is the need to observe the global circulation of the solar surface--differential rotation, global eddies or convection, and their variations in time over a solar cycle. This is needed because such circulation should be characteristic of the global flow within the convection zone, which in turn should be responsible for much of the amplification and maintenance of the sun's magnetic field. The velocity patterns of individual global eddies must be resolved, so that their interaction with the differential rotation and the magnetic field can be determined. We need to know how much the basic rotation of the sun influences the eddy structure, and which eddy sizes dominate in the flow pattern. We also need to know how persistent the eddies are in time--over one rotation to the next, and over a substantial part of the solar cycle. Are different kinds of eddies characteristic of different phases of the magnetic cycle?

Ground based measurements of global circulation of the sun using the Doppler effect have up to now defined rather well the average differential rotation of the sun. They have also given hints of time variations on a variety of time scales, but have told us practically nothing about global scale eddy motions. Global velocity measurements from different ground based observatories have been difficult to compare, because of contamination in the signal by short time scale solar noise, interference by the atmosphere, and instrumental effects. We mention below how space observations may overcome these difficulties.

Knowledge of how the eddies and differential rotation vary with depth is also of great importance because the sun's magnetic field is rooted beneath the photosphere, and most of the induction of the field takes place there. The radial angular velocity gradient plays a key role in many current solar dynamo theories. Extrapolations downward from the surface measurements must be made with the aid of theory. In this regard, it has recently been demonstrated that frequency splitting due to rotation in solar oscillations near 5 minute periods may tell us how the angular velocity varies with depth to 15-25 thousand kilometers below the sun's surface and perhaps deeper. This is because different modes of oscillation peak at different depths in the convection zone, and respond mostly to the rotation at that depth. In principle, these oscillations will also indicate how the differential rotation varies with time at these depths. The potential for global oscillations to reveal global convective eddy structure remains to be explored. Frequency splitting in those 5 minute oscillations with peak amplitudes very close to the surface can also be compared directly with the surface doppler rotation values.

Detailed interactions between the sun's velocity and magnetic fields are undoubtedly complex and occur on a wide range of spatial scales, but are not well measured. In order to examine interactions between velocities and magnetic fields in the photosphere, we need to measure the magnetic field to at least the same resolution as the velocity field, and at certain times to much higher resolution, since we already know much of the magnetic flux emerging at the surface is in the form of intense flux tubes. Solar dynamo theory demands answers to such questions as--Is the large scale movement of magnetic flux across the solar surface due to transport by the observed large scale velocity field, or are small scale interactions important, producing more of a "random walk"? Are large scale velocity patterns near active regions different than elsewhere? Are there certain velocity patterns which tend to be found in the neighborhood of coronal holes? Can horizontal divergence in the velocity field be found where new magnetic flux is emerging, indicating a region of upwelling which might have brought up the flux?

Global convection patterns on the sun should have associated small amplitude but persistent surface spatial variations in radiative flux. If large enough, these flux intensity patterns should also contribute to changes in solar luminosity. Slightly warmer fluid should be found where upwelling occurs. Changes in these patterns with time should be associated with detectable changes in the global velocity and magnetic field patterns. If the variations in the radiative flux could be detected, then they could yield information about the temperature structure with depth in the eddies, as well as provide another measure of subsurface rotation. The global oscillations can also yield information on the mean temperature structure with depth, as well as the depth of the whole convection zone.

III. Why Make These Observations from Space?

There are several reasons why the measurements need to be made from an orbiting platform. A prime reason is that the combination of bad weather and night time prevent us from getting the needed continuity of measurements from the ground. We argue this point in more detail below. In addition, differences in local seeing and atmospheric transparency as well as scattered light and short time scale noise of solar origin have made it extremely difficult to intercompare the ground-based observations which have been made, as well as making it difficult to separate what is solar in origin and what is not. This is particularly true of global velocity observations, but is also a serious problem in comparing magnetograph measurements. Luminosity measurements are clearly best made from space, to escape atmospheric scattering and absorption. We discuss the problem with respect to velocity measurements in greater detail, to illustrate the need for intense observations from space.

Progress in making global velocity measurements from the ground has been slow partly because of instrumental difficulties and atmospheric effects, and partly because there is a great deal of noise on the sun in the form of small scale motions (so called granulation, 5 minute oscillations, and supergranulation) which have larger amplitude than the global motions. Some of these difficulties may be overcome by improvements in ground based instrumentation, but others can be surmounted only by making frequent measurements from an orbiting platform.

We estimate that to resolve the velocities of global eddies, we need a basic measurement accuracy of between 1 and 10m/sec (a Doppler shift $\Delta\lambda$ of 2×10^{-5} to 2×10^{-4} Å at λ = 6000 Å). This precision can be obtained only by use of a wavelength reference against which to measure the doppler shift of the solar spectral line chosen. Otherwise various instrumental drifts mask the solar signal. Such reference techniques are currently being developed but have not been proven yet.

To reduce the small scale solar noise, the whole disk of the sun must be observed much more rapidly than is done by current systems. We estimate the time interval between observations should be no more than about 1 minute and preferably much less in order to average out the well-known 5 minute solar oscillations, requiring the use of some sort of "panoramic detector" which views the whole sun essentially at one time.

Averaging together observations made at 1 minute intervals over periods of 30 minutes to 1 hour should reduce the short time scale noise to the point that more persistent velocity patterns are evident. However even this is not enough, because the resulting patterns will probably be dominated by supergranules which last up to a day or two. To suppress these patterns and highlight the global eddies, we can average spatially, or take advantage of the fact that due to solar rotation supergranules move a distance equal to thier own diameter across the solar disk in a few hours (4 hrs at the equator, longer at higher latitudes). Thus by averaging over a few consecutive orbits supergranule velocities can also be reduced, though not eliminated. Then by comparing successive averaging periods, we can pick out the global velocities, which should not be cancelled out by the averaging process.

Comparison of velocities on successive days even with all of the averaging will be difficult because of residual noise and the rotation of the sun--more frequent samples are necessary. We need an essentially continuous record of averaged velocities, either as a succession of averages, or as a running average. In either case, this is achievable only from orbit, since night and bad weather prevent it from the ground. From the ground, observing runs long enough to largely cancel out supergranules would be achieved only occasionally.

Of course, new difficulties are introduced by going to space. For example, the velocity of the orbiting platform must be known to within a few meters per second, so it may be subtracted out, and stability of the instruments must be achieved.

Why a long term mission or series of missions?

The obvious answer to this question is that we are looking at the global dynamics of the sun over the course of a solar cycle, so we need to observe the sun that long. On the short time scale end, we expect changes on a time scale of a month or two, since that is a reasonable estimate for the turnover time for the entire convection zone. Furthermore, the basic rotation rate of the sun can be defined unambiguously only by averaging over at least one rotation (about 27 days). Over shorter times, a doppler rotation signal can not be distinguished unambiguously from other east-west motions of broad longitudinal extent. It is the changes in rotation, global eddies, magnetic fields, and intensity patterns from one rotation to the next, over the solar cycle, which are crucial to gaining an understanding of the workings of the solar dynamo. Therefore the space shuttle would be an inappropriate platform on which to make synoptic measurements, since observing would be limited to at most a few periods of one to two weeks per year. A free flying satellite, perhaps serviced periodically from the shuttle, would be far more appropriate. However, the shuttle could be very useful for test flights of some instruments, as well as for certain supporting measurements.

Observational requirements

As already indicated, we would like to achieve 1-10 m/sec accuracy in doppler velocities, with sampling rate fast enough to average out 5 min oscillations. Horizontal resolution should be $\sim$15 arc sec. But to study the oscillations themselves, we need to use all the data at a sampling rate of every 10 seconds or so. Ideally, we would like continuous observing runs of several days (possible with a high inclination orbit) in order to resolve finer differences in frequencies between waves. However, by suitable use of "apodizing functions" on data which is periodic gaps due to the orbit, such long strings can be put together with only modest loss of accuracy.

Magnetic fields need not be measured quite as often as velocities, but certainly at least once per orbit, to an accuracy of a few gauss, with spatial resoltuion of less than 10 arc sec if possible, since the magnetic field has so much fine structure. For intensity and luminosity measurements, we should aim for relative accuracy of .1%.

Supporting observations and theory

There are several observations related to those above, some to be made from space and some from the ground, which also need to be made. A particularly important one is the measurement of correlations between velocity and intensity, to very high spatial resolution ($\sim$.1 arc sec). Such a correlation is known to exist on the scale of granules, and may vary with time. It is relevant to the global velocity problem because such a correlation, particularly if it is time dependent, can appear like a large scale velocity. Such measurements are possible only from orbit with a high resolution telescope--these might be done periodically on Spacelab using the Solar Orbiting Telescope (SOT).

X-ray measurements of coronal structure, including particularly coronal holes are important for relating the surface magnetic and velocity fields. These are discussed more in the companion SCADM background paper by Holzer.

Both velocity and magnetic field observations should be done from the ground, for purposes of comparison for accuracy, as well as providing coverage if the satellite measurement system should malfunction at certain times.

To compare with solar velocity, oscillations, magnetic field and intensity measurements discussed above the relevant theory must be developed much further than it has so far. In particular, global convection and dynamo modeling must take into account compressibility, as well as small scale turbulence. Dynamo interactions between velocity and magnetic fields on smaller spatial scales will also need special attention. Global oscillations theory should be pushed to its limits, to see how deep into the convection zone information can be obtained, and to see how local the diagnostic inferences can be made.

THE CORONA AND HELIOSPHERE

Background paper for the Symposium on the Solar Cycle and Dynamics Mission, by T. Holzer, HAO

1. Introduction

The solar output in the form of electromagnetic radiation and low energy plasma (the solar wind) provides a driving force and an ambient medium for many physical systems in the atmospheres, ionospheres, and magnetospheres of the planets. Variations of the solar output lead to variations in the behavior of such planetary physical systems, and to gain a full understanding of these systems it is necessary to study the solar output and its variation. The eleven-year solar cycle is an especially appropriate period over which to carry out such a study, because during this cycle most of the important types of solar variability (many characterized by periods shorter than eleven years) are manifested. Studies of solar variability over a solar cycle will improve our understanding of solar structure and of the generation of the solar wind, and this improved understanding can be useful in the related studies of stellar structure and stellar winds, since stellar observations are necessarily less detailed and sophisticated than are solar observations.

A particularly significant benefit that will accrue from a thorough study of the solar atmosphere and its variability over the next solar cycle is a great enhancement in the usefulness of so-called 'proxy' data in studying longer term solar variations and their terrestrial implication. During the next solar cycle, it is anticipated that a coordinated satellite program studying the three-dimensional structure of the heliosphere and the terrestrial magnetophere, ionosphere, and atmosphere will be carried out through the Solar Polar Mission (SPM), a magnetospheric mission referred to as the Origin of Plasmas in the Earth's Neighborhood (OPEN), and the Upper Atmosphere Research Satellites (UARS) program. The addition of SCADM to this overall program will provide the opportunity for the first coordinated study of the full solar-terrestrial system through a significant portion of a solar cycle. Such a study will clearly increase our understanding of the 'proxy' data and their implications for the variability of the sun over the long periods of history and prehistory when relevant terrestrial data (i.e., 'proxy' data) are available but solar data are not.

The most highly variable part of the solar output consists of the solar plasma and energetic particle outputs and the short-wave-length portion (XUV, X-ray) of the electromagnetic radiation. This is the same part of the solar output that has a significant effect on the terrestrial magnetosphere, ionosphere, and upper atmosphere, so the study of its variability lies at the heart of the field of solar-terrestrial physics. A major goal of such a study is the understanding of the dynamics and thermodynamics of the sun's upper atmosphere, and SCADM can contribute substantially toward gaining this understanding (see section 3). The highly variable solar output is organized and substantially controlled by the structure of the solar magnetic field, which again is an area that SCADM is ideally suited to study (see section 2). Evidently, the control exerted on the solar output by the magnetic field determines the three-dimensional structure of the heliosphere, and the heliospheric structure, in turn, determines the access of galactic cosmic rays to the terrestrial environment. Of course, understanding the modulation of galactic cosmic rays is essential to an understanding of 'proxy' data and thus of the long-term behavior of the sun.

Although SCADM provides an extremely important mission on its own, if it is flown in coordination with other missions (viz., SPM, OPEN, UARS) its value can increase significantly. In conjunction with the polar passages of SPM, SCADM can provide a unique three-dimensional view of coronal structure. Together with the IPL of OPEN, SCADM can yield simultaneous solar and interplanetary observations pertaining directly to the problems of the acceleration of the solar wind, the origin of the He^3-rich and heavy-ion-rich solar energetic particle events, and the transport of energetic particles in the solar corona. Of course, SCADM, OPEN and UARS together can observe the variations in solar parameters relevant to the solar output and the simultaneous variations in the terrestrial magnetosphere, ionosphere, and upper atmosphere, which are systems largely driven by the variable solar output. SCADM should be timed appropriately to obtain these coordinated observations, and such timing would imply an early 1986 launch.

2. Coronal Structure and Its Evolution

The highly ionized plasma of the solar corona is, in essence, "frozen" to the coronal magnetic field, and since the coronal magnetic energy density is generally somewhat larger than the coronal plasma energy density below, ~ $2R_0$, the density structure of the plasma is largely controlled by the structure of the magnetic field. Unfortunately, it is very difficult to obtain direct measurements of the coronal magnetic field, and such observations are presently in a rudimentary state. In contrast, the photospheric magnetic field can be determined reasonably well through observation, but the deduction of the coronal field from the photospheric field remains problematic. Consequently, the best method of estimating the coronal magnetic geometry is through observation (in white light, EUV, XUV, and X-ray) of the coronal brightness structure, which is generally assumed to be magnetic-field-aligned.

An interesting example of the inference of large-scale magnetic geometry from the observed coronal brightness or density structure stems from the years 1974 -1975, in the declining phase of the past solar cycle. At that time the corona displayed a brightness structure similar in its overall features to the simple form expected in the presence of a magnetic dipole tilted by about 30^o to the axis of solar rotation. A band of bright corona, as observed in white light or X-rays, was inclined at 30^o to the solar equator with a prominent coronal hole near each polar cap, but appropriately displaced from the rotation axis. Association of the bright band with a belt of closed magnetic field lines and the two polar holes with open regions of opposite magnetic polarity suggests the existence of a similarly tilted magnetic neutral surface overlying the closed belt, separating the flow from the two polar regions. This description of a coronal magnetic geometry and the related solar wind flow unifies a large body of coronal, in situ interplanetary, and radio scintillation observations. In particular, rotation with the sun of the inclined neutral surface explains the simple two-sector magnetic polarity pattern observed in the ecliptic. This geometry marks a considerable departure from earlier ideas of north-south interplanetary sector boundaries; the implication of an important equatorial dipole moment is of interest in theories of the solar dynamo. (One should keep in mind the possibility that the different geometrical descriptions may be valid during different parts of the solar cycle.) Despite the attractiveness of this empirical model, the chain of reasoning connecting it to coronal and interplanetary observations involves several broad assumptions. Numerous questions concerning both its validity and its quantitative implications remain unanswered. For example, how does the low corona map out to the coronal streamers used to define the neutral surface at 2-3 solar radii, what is the coronal structure along that neutral sheet, and does the model truly reflect a basic simplicity common to the corona at similar epochs of other solar cycles?

This specific example of the association of coronal brightness or density structure with the geometry of the coronal magnetic field illustrates certain features of the solar magnetic field. If electric currents in the corona are weak, one expects the influence of small-scale features in the solar field (i.e., high-order components in a multipole expansion) to fall off rapidly with height. Thus the overall structure of the corona should be dominated by the largest-scale features in the solar magnetic field. Large-scale magnetic features are difficult to detect directly, as they involve weak average fields spread over large areas of the sun including the polar regions where the photospheric magnetic field is poorly measured. The basic form of coronal structure during the Skylab epoch has been interpreted in terms of discrete, large-scale features in the magnetic field (or low-order terms in a multipole expansion), drifting in the differentially rotating atmosphere. The evolution of this form to the simple, dipole-like structure mentioned earlier suggests an evolution of the solar magnetic field, perhaps associated with the solar cycle. Thus observations which could be made from SCADM would have implications not only for the study of the magnetic structure in the corona, but also for the large-scale features in the solar magnetic field. The temporal evolution of coronal features thus reveal the evolution of the magnetic field governed by subsurface processes (in the convection zone) that determine the photospheric field.

Implications for the heliosphere.

A striking illustration of the usefulness of X-ray, XUV and white light coronal data in an interdisciplinary area central to the goals of the SCADM mission comes from recent studies of coronal holes, solar wind streams, and interplanetary magnetic sectors. The origin of long-lived streams of fast solar wind (and the recurrent geomagnetic disturbances known to be associated with such streams) in regions of open, diverging, nearly unipolar magnetic fields was suggested almost 15 years ago. Studies correlating solar wind speeds and interplanetary magnetic sectors with observed photospheric magnetic fields (and their coronal extrapolations) strengthened this suggestion. However, the observation of such regions as coronal holes in X-ray and XUV studies over the past 5 years has placed this relationship on a sound basis by permitting association of specific solar wind features with specific regions of the sun. This allows, for example, comparison of the evolution of the proposed source regions and their interplanetary manifestations, and quantification of some aspects of the relationship. The observation of the spatial expansion of coronal holes with altitude by white light coronagraphs led to our present concept that solar wind flow from the polar regions of the sun can dominate the interplanetary stream and polarity structure even in the ecliptic plane. This latter realization again illustrates the importance of the combined SCADM and SPM observations; the three-dimensional view of both heliospheric and coronal structure is essential to understanding their relationship.

The nearly one-to-one correlation between coronal holes, including the equatorward extensions of the polar caps, and high-speed solar wind streams during the Skylab epoch shows that coronal structure can play a dominant role in modulating the outflow of solar wind. The identification of coronal holes with open magnetic regions where field lines diverge more rapidly than radial offers an attractive explanation for this role; theoretical models of field line guided expansion in such magnetic geometries reveal an extreme sensitivity of the speed of the wind to the rate of divergence in the lower to middle corona. Our strongest quantitative information on flow tube divergence comes from the study of a single polar hole observed during Skylab, for which a coronal density model and boundary shape has been derived from coronagraph and X-ray observations. Our strongest observational evidence for the role of field line divergence in governing the coronal expansion comes from a correlations between the area at the base of equatorial holes and the amplitude of associated solar wind streams also based on the Skylab epoch.

Such geometrical considerations obviously represent one of areas where the three-dimensional picture offered by a combination of SPM and SCADM observations would be most valuable.

Evolution of smaller-scale structure

The evolution of the solar magnetic field as observed at the photosphere presents two contrasting aspects. Magnetic features on spatial scales ranging from "bright points" through sunspots, to active regions seem to evolve through a stochastic process involving emergence at the surface, diffusion over an increasingly large area, and ultimate blending in the "general field". This general field, however, appears to be highly organized into large-scale patterns, as indicated by apparently regular patterns in the location and evolution of coronal holes and by the systematic changes in gross coronal morphology associated with the solar cycle.

The SCADM provides the opportunity to observe and relate the evolution of coronal features on different spatial and temporal scales. The small features known as "coronal bright points" have been observed in both X-rays and XUV. The largest, and longest-lived of them, are the "Ephemeral Active Regions" of photospheric magnetograms. Their role in the evolution of the solar magnetic field remains controversial. Skylab results show that, unlike the active regions, the bright point distribution on the disk extended from pole to pole. More recent rocket results imply that the total number of coronal bright points rises to a maximum near sunspot minimum and declines thereafter. The significance of this behavior lies in the estimate that the total amount of magnetic flux brought to the surface in the form of bright points during the Skylab period was comparable to that in the form of active regions. Thus the total magnetic flux at the surface at sunspot minimum might equal or even exceed that at sunspot maximum. Detailed observations from SCADM extending over a significant fraction of the solar cycle of bright point counts, distribution patterns and life histories will help us to understand these features and their role, if any in the solar cycle.

Coronal transient mass ejection events

Coronal transient mass ejection events are the most dramatic large-scale coronal evolutionary features. They can produce observable changes in coronal structure in a very short time (a few hours). Mass ejection events are observed in the lower corona in X-rays and in the middle and outer corona in white light. They are generally associated with eruptive phenomena in the chromosphere, often with solar flares. Estimates of the magnetic flux carried by the transients observed during Skylab suggest that they represent major rearrangements of the coronal magnetic field.

All of our estimates of the properties of transients, including the magnetic flux, are dependent on assumptions of their geometry. That geometry cannot be uniquely determined from a single view. The combination of perspectives by SCADM and SPM, however, would be able to distinguish between competing models (e.g., loops vs. spherical shells). An additional advantage would be the ability to determine the source of the transient unambiguously. The sources of half the coronal transients observed above the limb by a coronagraph will be invisible to an observer of the lower atmosphere (e.g., an X-ray telescope) located on the same line of sight. An orthogonal perspective alleviates this difficulty.

3. Dynamics and Thermodynamics of the Outer Solar Atmosphere

An essential tool for full understanding of both particle and radiative outputs from the sun is spatially and spectrally resolved observations in the XUV region of the spectrum. Such observations can in principle at the same time yield two quite distinct types of information, one dealing primarily with the low-energy plasma (solar wind) and the other primarily with the radiative outputs:

(a) XUV spectroscopic observations can give information on electron density, temperature, composition, and velocity of the coronal plasma. Knowledge of these properties, their spatial variation, and their evolution over the cycle is required to understand the coronal origin of the solar wind, and how and why the solar wind varies over the cycle.

(b) XUV spectroscopic observations yield directly the coronal radiative outputs at geophysically important wavelengths, and more fundamentally, should lead to an understanding of the origin of these radiations and their variations over the cycle.

We elaborate on these two distinct, but closely related, goals in the following discussion.

<u>The solar output of low-energy plasma: the solar wind</u>

The mass and energy flow in the solar wind, and thus the nature of the low energy plasma environment throughout the solar system, are determined by the topology of the coronal magnetic field and by the transport and dissipation of the non-radiative energy flux passing through the upper chromosphere and into the corona. Specifically, the nature and magnitude of the non-radiative energy flux passing outward through the upper chromosphere fixes the coronal base pressure, the coronal temperature, and (in magnetically open regions) the energy flux density in the solar wind. It is the coronal base pressure and the coronal temperature in the region of subsonic solar wind flow that largely determine the solar wind mass flux density.

Despite its fundamental importance in the acceleration of the solar wind, there presently exist neither adequate theories for nor direct observations of the generation of this energy flux and its transport through the solar atmosphere. However, it is possible to obtain some information about the role of the non-radiative energy flux in the acceleration of the solar wind by obtaining certain spectral observations of the transition zone and the corona. It is the developing ability to obtain high spectral resolution coronal line emission observation that makes this possibility so important to consider for all future solar space missions. Emission line spectra can give velocity, density, and temperature information for protons, hydrogen atoms, and heavier ions and atoms, while electron-scattered absorption line spectra can give electron temperature information. Velocity determinations, of course, provide the possibility of direct detection of the non-radiative energy flux (if it is carried by waves) while velocity and temperature determinations reveal the influence of the non-radiative flux on the solar wind expansion. The density determinations can provide information on elemental composition and ionization state in the corona, which, when compared with corresponding solar wind observations, can give some idea of the relative flow of the various ionic constituents and thus of the influence of the non-radiative flux on these constituents.

The origin and solar cycle variation of geophysically important UV and XUV emission

The measurement and prediction of UX/EUV/XUV irradiance is crucial to determining solar effects on the earth. Solar UV emission (1200 Å to 3000 Å) is important because it is completely absorbed in the upper atmosphere of the earth, such that any variations would lead to concurrent variations in the upper atmosphere--affecting the balance of sun-climate relations. Solar EUV/XUV emission (50 Å to 1200 Å) is important because it is the main ionizing source for the ionosphere.

A specific goal of the Solar Cycle and Dynamics Mission should be the observation of both solar outputs and their spatial structure in UV, EUV, and XUV spectral emissions--constituting portions of the spectrum inaccessible to observations from the surface of the earth. Solar cycle irradiance variations in these wavelength regions range from a fraction of a percent around 3000 Å, to about a percent around 2000 Å, to tens of percent around 1000 Å, up to factors of two and three around 100 Å. These variations have only been crudely observed, and are not understood. The irradiance variations are closely associated with magnetic field structure and energy transfer in the chromosphere and corona. For this reason, the temporal variations are like those for coronal and photospheric magnetic field structure. In order to understand the basic mechanisms of the emissions, it will thus be necessary to conduct observations concurrently with coronal scattered light observations, soft X-ray imaging, and photospheric magnetic field measurements. The temporal evolution is such that continual observations made several times per day, over a complete solar cycle, will be necessary to understand the solar cycle variation and to construct reliable models for predicting UV/EUV/XUV emissions during succeeding and prior solar cycles. We note that such observations may be carried out to some extent on other satellites (e.g., those intended primarily to study the terrestrial upper atmosphere) and there is no reason for SCADM to duplicate these.

The close relationship between energy transfer in the chromosphere/lower corona and EUV/XUV emission makes necessary the observation of line emissions in the 50 Å to 1400 Å range, with a spatial resolution of a few arc seconds. By observing appropriate lines in this spectral region, it is possible to determine temperature, electron densities, flow velocities, and some aspects of wave motion in the chromosphere and lower corona. The spatial resolution must be at least sufficient to isolate coronal holes, and preferably sufficient to resolve the chromospheric network--thereby resulting in the few arc second requirement. These observations of spatial structure supply boundary conditions for modeling coronal structure in association with observations of coronal evolution over a solar cycle, and futhermore provide the detailed structure information necessary for understanding the source and basic mechanisms for solar cycle variations of UV/EUV/XUV emission.

It is important to note that essentially the same data described above as being applicable to the understanding and prediction of particle outputs (solar wind) are also applicable to the understanding and prediction of radiative outputs.

PRESENTED PAPERS

OMIT

SYMPOSIUM ON THE STUDY OF THE SOLAR CYCLE FROM SPACE

Introductory Remarks

G. Newkirk

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Welcome to the Symposium on the Study of the Solar Cycle from space. As many of you are aware, a Working Group to examine the potential of space observations for understanding the solar cycle was convened last year. One conclusion of the Group was that a program addressing two major objectives of understanding:

- The fundamental mechanisms of the solar cycle, and

- The effects of the solar cycle on the heliosphere and the atmospheres of the planets

is particularly timely for the 1980's.

The timeliness of such a program arises from several factors:

- Our perceptions of the sun have evolved dramtically in the last few years. We are now aware of the fact that solar activity in the distant past was both much higher and much lower than anything we have experienced in the last 300 years. The scientific era has sampled only about 10% of the dynamic range of solar activity. Recent measurements suggest that the integrated radiant flux of the sun is not constant. Even the diameter of the sun appears not to be constant - it may be shrinking 1 to 2 seconds of arc per century! And, of course, the neutrino problem stubbornly refuses to be resolved.

- Coupled with the crumbling of simplistic notions about the sun is the emergence of an arsenal of new tools for understanding the sun and its magnetic cycle. For example, proxy data such as ^{14}C allow us to trace the envelope of solar activity back 5,000 years, and other radiogenic isotypes promise the extension of our record of solar activity back to about 10^5 years. Large scale computers now permit the development of numerical models of the circulation in the connective layers beneath the visible photophere. Thus, quantitative models of the operation of the solar magnetic dynamic, which derives the solar cycle, are becoming a reality. New diagnostics of oscillatives of the photosphere allow us to probe the structure of the invisible interior, and now feasible measures of the large scale circulation of the photosphere, promise to provide both the essential boundary conditions for these newly emerging mathematical models as well as the possibility of discovering entirely new solar phenomena.

Thus, the 1980's appears to be the decade when we will finally reach an understanding of one of the most fundamental process of nature - the operation of the solar cycle.

The purpose of this Symposium is to identify the most compelling problems in this area of solar physics and to examine how these are to be addressed. In particular we will be concerned with the role space observations will play in this exciting venture. We hope that our discussions will bring into sharper perspective the strategy we should persue in the coming decade as well as the crucial missions, experiments, and theoretical advances which will be required to achieve our goal.

With that brief introduction I turn the platform over to the first invited speaker, Dr. Robert Noyes, who will examine in depth the objectives of a SCADM.

N80-17947

OVERVIEW ON THE STUDY OF THE SOLAR CYCLE FROM SPACE

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I. INTRODUCTION

The nature of the solar cycle is one of the most outstanding and long-lived problems in astrophysics. Sunspots have been intensively studied since the first telescopic observations in 1610, and the cyclical nature of their appearance has been known since 1843. Sunspots are the solar features best known to the general public, and the 11-year sunspot cycle is now a topic of everyday conversation. The wealth of detailed observational material on the solar cycle, including the butterfly diagram, Hale's law of polarity, differential rotation, and many other less obvious aspects of the cycle, is truly impressive. No less impressive is the fact that a number of phenomenological models have been produced that rather plausibly explain and interrelate this vast set of data; of these, Babcock's model in the late 50's is probably the best known. Until recently, however, the tools were not at hand to make a detailed theoretical model, that predicts rather than explains the observed phenomena and for this reason the nature of the cycle must still be ranked as an unsolved problem.

The importance of the problem far transcends the field of solar physics. That other stars might have cycles was inferred long ago simply on the basis that the Sun is in every measurable way a "typical" star. This led O. C. Wilson to begin his pioneering work over a dozen years ago on monitoring the K-line in stars in order to see if cycles might be detected in other solar-like stars. This work has recently culminated in a landmark paper that shows unmistakable evidence for cyclic activity much like that of the Sun in a variety of late-type main-sequence stars. At the same time, stellar activity that seems to be in many ways analogous to solar activity--flares, starspots, and hot coronae--have been detected both by ground-based observations and ultraviolet and X-ray space observations. Clearly, activity and its quasi-cyclical variation is a major fact of stellar life, and if anything, the activity cycle we follow with such great detail on the Sun is but a weak imitation of larger-amplitude activity cycles on many other stars. Hence, understanding the solar cycle has great importance for stellar astrophysics in general.

For many years, quite independently of the astrophysicists, the geophysical community has been investigating the effects of the solar cycle on the terrestrial environment, including the interplanetary medium, the magnetosphere, the ionosphere, and the atmosphere of the earth. The imprint of the activity cycle on the solar wind and on a host of related geomagnetic effects scarcely need be mentioned to this audience. Many of the effects of the solar activity such as magnetospheric perturbations, aurorae, and other geomagnetic effects, are generally understood, but others are not, due in part to a lack of knowledge of the detailed solar output as a function of phase of the activity cycle.

In addition to such well-documented effects, whether understood or not, there are several other suspected effects of the solar cycle on the earth, such as the possible effects on climate hinted at by tree ring data and other climatological indicators. In spite of many years of work, the evidence for a causal relationship is not yet fully convincing. Nevertheless the problem cannot be dismissed because of lack of progress, because if a physical relation does exist it is of tremendous practical importance.

It is clear then that a deeper understanding of the nature of the solar activity cycle, its physical origins and its effects on the heliosphere and the terrestrial environment, will be of extreme importance both to astrophysics and to solar-terrestrial physics, and any new opportunity to make a major advance in our knowledge of the cycle should be securely grasped.

Many scientists believe that such a new opportunity does exist, and this is the main reason for the present symposium to explore the question in depth. What is the nature of the special opportunity that exists today? After all, as we have already mentioned, the solar cycle is already one of the most exhaustively studied of astrophysical phenomena. However, three recent developments have come together to allow for a new and more vigorous approach to the problem:

First and foremost is the remarkable recent outpouring of new information about the solar interior and its cycles--some of which has upset concepts that have been taken for granted for generations of astronomers. It is worth listing some of these:

1) The neutrino deficit shows we do not really understand the "zero-order" structure of the solar interior or its energy generation mechanism.

2) The rediscovery of the Maunder Minimum shows that the activity cycle is even more irregular than previously realized, and in fact can apparently effectively vanish altogether.

3) During the Skylab era, bright points were discovered that were subsequently found to carry to the surface an amount of magnetic flux comparable to that in the much larger but less numerous active regions, and, surprisingly enough, approximately out of phase with the active region magnetic flux. Thus the total magnetic flux emerging from the interior may not vary at all during the cycle!

4) The rotation and differential rotation of the Sun has been found to be far from constant, apparently varying greatly in association with the Maunder Minimum, and perhaps by a lesser amount in connection with "normal" activity cycles.

5) It appears that the solar constant, long suspected of actually being inconstant, has now been measured to undergo significant changes with the solar cycle.

6) During the Skylab era, observations of coronal holes and of the solar wind showed holes to be the sources of high-speed wind streams, and those data combined with follow-up ground observations produced a very satisfactory picture of the evolution of coronal and interplanetary magnetic field structures over the cycle in response to subsurface motions.

7) As already mentioned, activity cycles have recently been discovered in a number of solar-like stars, and we may anticipate that shortly new insights (such

as the relation between rotation period and activity cycle period) will emerge from study of these stars.

Such new revelations cannot fail to rekindle our interest in the solar cycle, and at the same time suggest new concepts and new approaches to understanding it.

A second recent development that gives hope for new progress in understanding the cycle is the development of new observational techniques to measure subsurface phenomena, that in turn can reflect the workings of the subsurface dynamo. Probably the best example is the development of studies of the well-known solar five-minute oscillation as a tool to probe the structure of the outer convection zone. The rotational splitting of the eigenfrequencies of oscillations at various wave numbers reflects the angular velocity at convection zone depths appropriate to those wave numbers, and thus can yield the variation of angular velocity with depth. Similarly, studies of longer-period global oscillations should lead to knowledge of physical conditions at greater depths, using the techniques of "solar seismology." Another observational advance of great potential importance is the capability to measure extremely low velocities--in the range of 10 m/sec or less--that may reveal slow meridional circulations or upwellings of giant convective cells in the convection zone. The level of precision of solar irradiance detectors is approaching that required for measuring the solar luminosity changes associated with sunspots, plages, giant convective cells, or other large-scale circulations. Other examples of new observational techniques relevant to studies of the cycle could be given, and because of intense current interest in the problem, new techniques are continually being developed.

The third new development giving hope for major near-term progress in understanding the solar cycle is the creation of new numerical techniques to model the cycle theoretically using modern, high-speed computers. This capability should allow us to formulate more precisely than ever before the critical questions which must be attacked observationally in order to discriminate between various theories of the cycle.

The above three considerations argue strongly that the time is ripe for further progress in understanding of the solar cycle. Given these arguments, one might still ask why we should plan a concerted attack on the problem, rather than relying on the individual efforts of scientists working separately, in the style that has led to most of the progress in the past. One reason is that a study of the cycle must be, by its own nature, a long-term program lasting at least a significant fraction of the cycle itself, perhaps transcending the length of effective contribution of individual scientists. Furthermore, the subject is such a large and complex one that coordinated efforts of a number of scientists can be expected to yield far greater results than their separate independent efforts. Finally, a key component of any new scientific attack on the nature of the cycle will involve observations from space and hence will require the deployment of large resources. It might be added that a program of this magnitude and duration will probably be carried out only once in the foreseeable future, so it is of great importance that plans be laid correctly.

We have argued above that the science of the solar cycle is important, is timely for a new attack, and requires a large-scale concerted program for optimum progress. The proof of any pudding is in the eating, however, so we must focus on the key question of what ultimately will result from a large-scale program to study the solar cycle; this is really the subject of the current symposium. The most compelling science in the world is of little practical interest unless we can formulate key questions in a way that then realistically can be answered by experimental or theoretical investigations. Formulating the key questions and providing the right technology are difficult and exciting challenges, which must be met in the earliest stages of defining a program. Of course, in meeting these challenges the theorist and experimenter (who may be one and the same) work together: what is technologically feasible allows the selection of a subset of scientific questions from the totality of all that are interesting, and the most important scientific questions stimulate the development of a subset of key experiments from a larger group of technologically conceivable ones.

When all is said and done and a program is finally hammered out, the most important question remains: is it really worth its salt? In other words, how does it compare with other worthwhile programs that will compete for the dedication of the scientific community and the available resources?

The program to study the solar cycle is in its early, formative stages. The scientific opportunities have been widely recognized as outstanding, and much of the appropriate technology either exists or seems readily developable. However the marriage of optimum scientific questions and the required technological tools has not yet been carried out, and this must be a key activity over the coming months as the program becomes better defined.

In a few moments other speakers will discuss individual scientific or technical questions in detail. Before that, however, let us take a brief broader look, first at the overall scientific goals and then at the broad characteristics of a program designed to accomplish these goals.

2. THE TWO MAIN SCIENTIFIC GOALS OF A SOLAR CYCLE PROGRAM

It is helpful to consider that the goals of studying the solar cycle may be divided into two groups: In oversimplified terms, these may be labeled as understanding the causes of the solar cycle, and the effects of the solar cycle. By causes, we mean the physical origins and mechanisms of the solar cycle. By effects we mean how the mechanisms of the cycle affect the heliosphere--that vast region that includes the corona, interplanetary medium, and the terrestrial environment. (This distinction between effects and causes is valid because the heliosphere is essentially the tail wagged by the solar dog--it does not seem to work back and control in any significant way the cycle itself.)

The causes of the cycle are clearly rooted in the subsurface layers, which we cannot observe directly. This simple fact means that the more fundamental of our two goals is also the more difficult. However, the developments mentioned earlier as permitting us to make a renewed attack on the cycle are particularly germane to understanding its causes. The recent insights into the workings of the cycle have already given us many leads as to the directions our research should take in understanding the dynamics of the interior, and have materially increased the richness of the data applicable to inferring subsurface dynamics. The new techniques that we have mentioned, such as solar "seismology," or the capability of measuring extremely low velocities, give promise for new types of findings about subsurface dynamics. Finally, the recent developments of theoretical and computational techniques add a significant weapon in attacking problems of the origin of the cycle. In fact, theory finds itself playing an unusually prominent role in this problem, just because we are studying regions of the Sun that cannot be observed directly. For the first time in the history of solar astronomy the theorist may have more to say than the observer about the problem at hand! In framing our program we must keep in mind that the role of the theorist is essential, both in defining the experiments as well as in interpreting them.

By way of illustrating more concretely types of investigations that address the causes of the solar cycle, I list here only some of the many observational programs that have been suggested as likely to provide important information on the mechanisms of the cycle:

1) Determination of depth-dependence of angular velocity from splitting of normal modes of short-period global oscillations, and improvement of models of the deep convection zone from long-period global oscillations.

2) Study of differential rotation of magnetized and nonmagnetized plasma as a function of latitude, longitude, and phase in the cycle.

3) High-resolution (sub arcsec) observations of magnetic and velocity fields at the photosphere in order to provide boundary conditions for theories of magnetic convection.

4) Moderate angular resolution, high sensitivity, synoptic photospheric magnetic field observations, to determine coronal field configurations (e.g. their connectivity) and their evolution over the cycle; ultimately to relate these to subsurface field geometry.

5) Moderate angular resolution, high sensitivity synoptic low-velocity measures in the photosphere, to detect meridional flows, giant cells, or other circulation patterns and their evolution.

6) Synoptic studies of bright point distribution, and its evolution over the cycle, with special attention to the relation to velocity flows (e.g. giant cells or other circulations) and to large-scale magnetic features.

7) High-precision study of the solar luminosity (solar constant) variation over the cycle, and its relation to sunspots and plages, as an indicator of cycle- or activity-related modulation of convective energy flow.

8) Synoptic study of the rotation and evolution of coronal holes throughout the cycle, in order to understand the subsurface driving function that gives rise to these features.

We turn now to the effects of the cycle on the corona and the heliosphere, and on the terrestrial environment. This question is to be differentiated from the more traditional question of how solar activity itself affects the heliosphere and terrestrial environment, for here we concentrate on the response to the solar cycle-induced variability of activity. This different emphasis distinguishes a solar cycle study from previous studies of solar-terrestrial relations.

Examples of studies of the effects of solar cycle variations include:

1) Study of the solar cycle-dependence of non-radiative energy input into the chromosphere and corona, as an indication of how acoustic flux, magnetic structure, and magnetic energy dissipation varies with the cycle.

2) Study of the evolution of coronal structure and dynamics in response to the above cycle-related inputs, with particular application to the formation of coronal holes, high speed solar wind streams, etc.

3) Study of how globally-averaged UV and X-ray emissions, known to affect the terrestrial ionosphere and atmosphere, vary in response to the cycle, and identification of the solar sources of these emissions and their variations.

Observations in pursuit of this goal relate more or less closely to several other programs, for example, the OPEN (Origin of Plasma in the Earth's Neighborhood) program, the IPL (Interplanetary Physics Laboratory) satellite, and the UARS (Upper Atmospheric Research Satellite); coordination with such programs is clearly required. An important new ingredient of a solar cycle program that goes beyond the scope of these programs is the detailed study of the solar origins of observed terrestrial effects, and the long-term variations of those parameters that produce terrestrial effects.

Observations in support of our second goal will produce a broad data base on all aspects of solar cycle behavior and its variations, including EUV and X-ray fluxes, cosmic ray variations, aurorae, geomagnetic responses, and so forth. This information will serve as a template for proxy studies of earlier data (tree rings, aurorae, etc.) that can help extend the record of solar activity backwards many centuries in time, and thus can indirectly contribute to the first goal of understanding the nature of the cycle, through inferring its long-term history.

It should be stressed that the short lists given above as examples are by no means exhaustive. The examples do share the property that all observations are possible using existing or very foreseeable technology.

3. THE NATURE OF THE SOLAR CYCLE AND DYNAMICS MISSION

A key characteristic of the observational part of a solar cycle program designed to attack the two above goals is immediately apparent; the program must last at least a significant fraction of the solar cycle, and observations must be made frequently enough to iron out fluctuations due to individual centers of activity. Thus at the very minimum a series of observations would be required, each lasting many rotations, and together covering as large a fraction as possible of an entire cycle. More desirable, of course, would be a program of observations obtained essentially continuously over an entire cycle.

This puts several stringent requirements on the program: a) on the scientists involved, who must have the patience and the long-range view to carry out observations that last years before the final results are in; b) on instrumentation, which must be designed and operated in a stable, reproducible way over a long time (this fact means that instruments must be designed as close to the state of the art as practicable, since once launched, the requirement of continuity of data makes it harder to upgrade them significantly later); c) on program management, especially that part (SCADM) which is carried out from space. A single free-flyer lasting many years, while possible, is technologically difficult and has the additional difficulty that it requires a NASA budgetary commitment to a many-year effort. Successive flights with periodic refurbishment are possible but introduce many other problems in continuity and calibration, as well as severe loss of data.

Another important aspect of a program to study the solar cycle is the breadth of techniques that should be used. Although SCADM is a space mission, it should be thought of as embedded within a wider <u>program</u> of solar cycle research, that encompasses space observations from a variety of spacecraft, ground-based observations, and throughout the program intensive theoretical activities that provide the rationale for the observational efforts, as well as the means of their subsequent interpretation.

The broad solar cycle and dynamics program may be described as an optimum mix of theory, ground, and space observations that best accomplishes the overall scientific goals. All three components are critical, and if such a program is to succeed there has to be careful coordination and interplay between all three.

Because of the high cost of space observations, it is obvious that observations in support of the solar cycle and dynamics program should in general be carried out from the ground, unless space observations are absolutely essential. Several of the potentially important experiments listed above involve the analysis of visible radiation and hence in principle could be carried out from the ground; on the other hand difficulties associated with the atmosphere or the terrestrial day/night cycle could make some ground observations impossible in practice, and thus, if the observation is sufficiently important dictate observations from space.

We have already noted the planning for a number of space missions, that contribute to a greater or lesser degree to the goals of a solar cycle and dynamics program. Among these are OPEN, UARS, IPL and the International Solar Polar Mission (ISPM). Clearly the solar cycle program should be structured to make optimum use of these and other related missions. Thus, observations from SCADM should be planned in coordination with ISPM if possible, to provide information on the three-dimensional structure of the corona that would otherwise be unavailable.

One aim of this symposium should be to explore ways to optimize SCADM as viewed in the context of a larger program. These comments, while obvious, are critical in making mission tradeoffs--for example, between ground-based and space techniques for performing a particular type of observation.

I wish to conclude with a few general remarks about the nature of the SCADM mission itself, now seen as the principal space component of a broader solar cycle program.

First, although SCADM should be embedded within a broad solar cycle and dynamics program, the space mission should be very narrowly focused. The inevitable cost constraints suggest that the number of experiments flown will be severely limited, so only experiments that contribute directly and critically to the mission goals and that cannot be performed from the ground should be flown. A good model for SCADM is the Solar Maximum Mission, which was endorsed by the scientific community and by NASA because it was a well-focused, problem-oriented payload.

Second, a key attribute of the mission is its ability to function over a significant fraction of the solar cycle. The nature of the experiments as well as the mission are significantly affected by this requirement.

Third, and most important of all, the experiments must be chosen to answer well-posed questions or test specific theoretical predictions about the nature of the solar cycle. In this context we reemphasize the unusual role played by theory, in bridging between observations of surface phenomena and inferences of subsurface properties.

4. SUMMARY AND CONCLUSION

In this talk I have attempted an overview of the key attributes of a program to study the solar cycle, and a SCADM mission as part of that program. Principal conclusions are:

a) The nature of the solar cycle is one of the most important unsolved problems in astrophysics and solar-terrestrial physics today.

b) The time is scientifically ripe for a large-scale experimental-theoretical attack on this problem.

c) The solar cycle program, and the SCADM mission, should attack two broad goals, which can be simplistically described as the causes and the effects of the solar cycle. A number of specific questions can be posed directly addressing these issues, for which technical capability of resolving them is at hand.

d) Such an attack should be by way of a well-planned solar cycle research program, incorporating theory, ground-based observations, and space observations. The last would involve a special-purpose Solar Cycle and Dynamics Mission (SCADM), as well as coordination with a number of other currently-planned space missions.

e) The SCADM mission should be narrowly focused, to a problem-oriented payload whose experiments are chosen to answer well-posed theoretical questions about the nature of the cycle and its effects. A key characteristic of the mission should be its ability to obtain synoptic data on solar variability associated with the cycle, over at least a significant fraction of a single 11-year cycle.

I close by recalling, and respectfully disputing, a comment by Dr. Parker yesterday, to the effect that study of solar and stellar variability is long and hard work and not very glamorous. While it is admittedly long and hard work, I sense that the astrophysical and geophysical community have achieved the maturity of vision that sees the importance, and even the glamour, of such fundamental research as we will be talking of in this symposium.

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MISSION OPTIONS FOR SCADM IN THE 1980's

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ABSTRACT

There are a number of possibilities for the type of spacecraft and orbit which could be used by a major solar physics mission in the 1980's. The final selection will depend on the specific scientific objectives of the mission, which have not yet been defined in detail, and on the mission support requirements that they imply. Some of the spacecraft options that have been studied to date include: 1) a modified version of the Solar Maximum Mission spacecraft, perhaps using refurbished components of the SMM itself, 2) a Shuttle Optimized Spacecraft, presently being considered for development as a standard support structure, and 3) a portion of a Space Platform, possibly one dedicated to solar investigations, or perhaps as a part of a Solar-Terrestrial Observatory. Selections of orbital altitude and inclination involve trade-offs between payload weight, telemetry rate, cost, and time in daylight, as well as considerations of thermal stability, velocity variations, and ease of retrieval or in-orbit refurbishment. All of the options being studied would use the Space Transportation System (STS) for launch, and most would communicate with the ground through the Tracking and Data Relay Satellite System (TDRSS), both of which will be standard NASA systems by the mid-1980's.

QUESTIONS AND COMMENTS

COMMENT BY: R. J. Thomas, Goddard Space Flight Center

DIRECTED TO: David Bohlin

I would like to add that the Shuttle Optimized Spacecraft would be able to carry some very long instruments. In fact, it can accommodate instruments as long as 4.5 meters, which are considerably larger than those flown on the Skylab ATM. The weight allowance for experiments is also large. Therefore, SCADM will permit some major-sized instruments on a long-term free-flying spacecraft for the first time in the solar space program.

N80-17948

A SOLAR ACTIVITY MONITORING PLATFORM FOR SCADM

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The Solar Cycle and Dynamics Mission calls for a dedicated earth-orbiting spacecraft series providing platforms for multiple sensors yielding not only high quality photospheric observations of solar velocities, magnetic fields, intensity patterns, luminosity and various radiative outputs, but also measurements of associated particle and X-ray fluxes. These data would be obtained by optical as well as other techniques over a wide range of the spectrum. As pointed out by P. A. Gilman in his summary paper (Ref 1) of the SCADM Study Group, the SCADM observations must be nearly continuous in time and of long duration--most or all of a solar cycle. Gilman also notes that "theoretical and computational tools and models have now reached the point that quantitative modeling of the global circulation of the sun and its dynamo action is within reach, so that much better information than now exists on global solar velocities, magnetic field and intensity patterns is needed for comparisons with such models." These detailed data from the SCADM spacecraft will, however, see no more than one-half the global solar events since only half the sun's surface can be seen by either ground or arth orbital instruments. When combined with optical data from the Solar Polar Mission (SPM) and other wide-ranging but non-optical probes, three-dimensional structure of the heliosphere and terrestrial neighborhood will result. Our paper summarizes a study made in 1973 addressing a different application of solar-monitoring, one which we suggest has direct bearing on the SCADM data base if it were implemented.

At the Seattle COSPAR meeting in 1971, an informal discussion with the late Dr. Leen de Feiter of Utrecht, Prof. P. Simon of Observatoire de Paris, and Dr. P. Tanskanen of Finland addressed the 14-day gap inherent in the solar data used to forecast solar-geophysical activity. This

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"backside" gap is one specifically addressed by the Space Environment Services Centre in Boulder in Ref. 2. Its elimination "would materially improve the quality of 3 to 5 day predictions of solar activity". We suggest it would add great balue to the SCADM data base.

The following year one of us (DDR) undertook the adaptation of then-current, proven space-probe technology to provide a Solar Activity Monitoring Platform (SAMPL) which could be injected behind the earth's orbital position to give three to six days advanced coverage of the solar phenomenon on the backside hemisphere which would soon rotate into view and thus affect terrestrial activities. It would also provide some three-dimensional discrimination within the ecliptic latitudes. We believe the study indicates that a relatively simple off-earth probe could provide valuable data of very high quality for support of the SCADM program. The basic spacecraft concept is configured around two small optical systems for monochromatic imaging of either a whole hemisphere or, with increased resolution, of active regions. It might also incorporate solar magnetographic equipment using a non-dispersing polarimeter. We have not undertaken a design concept for such a magnetograph system. The SCADM spac[illegible] will need such a device, one which might fit the physical limitations of the SAMPL spacecraft. Our 1973 key goal was a simple low-power, passive [illegible] of long lifetime and high stability, one which utilized [illegible] mission-proven technology. A 1980's implementation would incorporate better technology in specific systems, but would not alter [illegible]. We see this same concept of a probe, capable of transmi[illegible] both high-resolution video data of the solar surface and [illegible] of solar activity as particle, X-ray, ultraviolet, and [illegible] fluxes as invaluable to the SCADM program, particularly i[illegible]ments are tailored to SCADM problems and observation pe[illegible]

The Orbit

The basic SAMPL mission is illustrated [illegible] vehicle position, roughly on the far side of the sun, wou[illegible] the solar hemisphere invisible to earth. Combined with [illegible] observations, almost the entire surface of the sun would be [illegible] surveillance, providing data continuity for global solar resea[illegible] spacecraft were truly on the far side, collinear with the earth and [illegible], the [illegible] perspective would be poor, a disadvantage to the solar forecaster. In order to provide good video data for both the solar research and the solar forecaster with a single vehicle, a compromise position of the spacecraft should be used. Solar rotation direction dictates that the SAMPL be placed at some lag angle behind the earth. Dr. Frederick Ward of the Air Force Geophysics Laboratory (private communication) indicated that the satellite should be placed at a 120-degree lag angle in order to benefit the solar forecaster.

The spacecraft orbit should be selected such that:

a. near-circular heliocentric orbit with semi-major axis slightly greater than 1 AU.

b. orbit plane in the ecliptic

This will allow slow, regular drift in solar longitude trailing the earth with minimum energy of escape/transfer. Rather than stabilize the vehicle at a constant lag position, requiring another major orbit transfer many months after launch, requiring additional control and vehicle propellant, we suggest that a series of vehicles should be launched about three to four years apart and allowed to drift slowly through 60-180 degree lag angles during their lifetime. This orbit is depicted in Figure 1B.

The Vehicle

The requirements and characteristics of the mission place several stringent constraints on the SAMPL spacecraft. Lifetime must be on the order of five years for reasonable data return. The long-focus optical system necessary for video imaging requires telescope pointing in the 1-arc -second range. It is desirable to meet this latter requirement by pointing the vehicle itself. The attitude-control system should be inherently stable, even with a partial failure in the active control circuitry. Finally, the separation of the satellite from earth by distances up to 2 AU constrains the vehicle in two ways: first, the video transmission over long distances requires both a high-gain spacecraft antenna and a relatively high-powered transmitter, 100 watts. The second is radio transmission time lag, up to 16 minutes for a one-way trip. About 30 minutes might be required for an earth-based experimenter to respond to something seen in the data. A solar flare can rise from zero to maximum brightness in less than two minutes. Thus, the satellite must be highly autonomous, or able to change automatically its sensor sampling process, in order to relay back important flare rise data. Figure 2 illustrates this communications concept.

Subsystems

Postulated for the SAMPL spacecraft were subsystems for monochromatic imaging of the sun at two nearby wavelengths for particle/photon detection, for necessary data conditioning and transmission, and for spacecraft stabilization sufficient that the final image stabilization could occur in the optical imaging sensor itself. Only the optical imaging sensors and the stabilization system concept will be discussed here since all others were adopted directly from other flight hardware. Table I gives a summary of the key subsystems and their source.

TABLE I. SUB-SYSTEMS AND THEIR EMBODIMENTS

Data Processing and Transmission:	Mariner IX, 800 bits/sec, 100W
High-Gain Antenna:	2-meter Harris furlable, 27db gain
Computer:	OAO-C, 64K core
Propulsion:	Upgraded Mariner IX
Optical Sensor:	Skylab ATM Varient w/Image Dissector, 21cm, f/16
Charged Particles:	Small Sci Sat - S^3
X-ray/UV:	OGO-F
Radio Flux:	No Equivalent
Stabilization System:	Vehicle Shadow Modulated. Radiation Pressure Boom based on Commandable Gravity-Gradient System.

A frontal view of the SAMPL spacecraft main body is shown in Fig. 3 to indicate relative sizes and possible locations of important subsystems.

Optical Imaging Sensors

The optical imaging subsystem consists of two telescopes with narrow-band filters and image-dissector tubes, a modification of the ATM telescope built for the Skylab mission (Ref 4). One of the SAMPL telescopes has a band center at the 6563 Å Hα line, while the other views the sun in the emission continuum about 5 Angstroms away. Since both filters are temperature sensitive, the SAMPL filters are maintained at constant temperature by a heater system with feedback control. In a backup mode, the continuum filter can be thermally re-tuned to the Hα band center if the Hα telescope fails.

The ATM telescope incorporates a heat-rejection window along with two phase-coherent Fabry-Perot interferometer filters using a solid fused-silica spacer. This combined filter has a 0.75 Angstrom bandwidth and a passband transmission of about 50 percent. The ATM telescope uses an f/4, 6.5-inch primary mirror with a secondary mirror/field corrector lens combination, and a transfer lens to give an overall speed of f/30. Images were recorded on film.

The SAMPL telescope proposed a varient system using instead an f/2.4, 8.5-inch primary mirror, secondary mirror and field corrector lens combination to achieve an overall speed of f/16.4. Transfer lenses are used to improve filtering. The MTF of the resulting system is about 0.25 at a resolution of 1 arc-second. Fig. 4 shows the video sensor.

The suggested imaging device is an image dissector with a 1.7-inch photocathode, magnetically focused and deflected with digital control. The position repeatability of the scan can be better than 1 arc-second on the solar image, and extensive scan programming is possible using the spacecraft computer. The weight of the optical imaging system itself is expected to be about 40 kilograms. The solar disk will subtend about 70% of the field of view and will be stabilized to less than 1 arc-second.

Three modes of video operation are seen. The first is a scan of part of the solar disk, extending from 45-degrees north to south polar latitudes, at a resolution of 2 arc-seconds. These boundaries encompass most of the flare active regions which appear. The readout for a 2 arc-second element interrogation rate of 140 elements per second is about 1 hour. This mode of operation provides a general mapping of large solar activity regions once or twice per day in normal circumstances.

A second mode of operation involves scanning a small raster whose size and location are programmable by command or by the flare search mode to be described below. The raster is scanned at the full resolution of 1 arc-second and provides a detailed view of limited areas. The data rate in terms of resolution elements is also 140 elements per second.

A third mode of operation, which might be called a "flare search" mode is actually a rapid, 20 arc-second resolution scan of the entire disk. The output of the sensor can be sent to earth, but it is checked automatically for the 20 arc-second regions in which the brightness exceeds a programmable level. If exceedences are discovered during the scan, which only takes about 15 seconds, the normal scan operation can be interrupted and a series of localized raster scans in the areas of interest begun. This series of scans provides a time-sequenced view of the rise phase of flares. This flare search mode can be interleaved into a normal raster scan periodically, and other data transmitted during the 15-second gaps. The original scan can be resumed at the point of interruption.

Time-shared with the above modes are check scans of the solar limb at cardinal points of the disk to check for spacecraft attitude drifts to both (1) stabilize the scan pattern and (2) provide input for the momentum dump to the radiation pressure boom (Ref. 3, pp 45-48).

Radiation-Pressure Attitude-Control System

The SAMPL concept requires of the attitude control system: (1) arc-second pointing accuracy, (2) inherent passive stability, and (3) five year lifetime. (1) is met only by the attitude-control systems on some observatory-class spacecraft, systems using combined reaction wheels and gas thrusters, both lifetime-limited. No existing attitude-control system met all three requirements, so a novel adaptation for an attitude-control system was included in the study.

For inherent passive stability, attitude-control by torque interactions between the vehicle and its environment must be used. Possible interactions are solar wind aerodynamic torques, radiation pressure torques, heliocentric gravity-gradient torques, and magnetic dipole interactions. Radiation-pressure torques were found to be largest by a factor of 10^3. The adopted design utilizes an adaptive array of reflectors on an arm extending radially away from the sun behind the satellite (Fig. 5), operating in the same general manner as an arrow in flight. Feathers at the end of an arrow apply restoring torques about the heavy arrowhead. The boom reflector system applies restoring torques about the vehicle center of mass when the boom departs from the solar radial. This restoring torque will "anchor" the boom along the radial when a damping system is added. Other reflector systems provide roll-axis control and null any static radiation pressure assymetries. The concept was based on two well-established systems, the DeHavilland boom and the Commandable Gravity-Gradient System developed for attitude control on one of the ATS vehicles (Ref. 5). In the COGGS system, the boom is attached to the satellite by a two-axis free pivot with torque motors about each axis. With this arrangement, attitude position and rate errors can be transferred from the vehicle to the boom by the torque motors. A boom used in this manner is called a reaction boom whose theory is found in Ref. 6. The reaction boom concept in SAMPL provides rapid, dynamic correction of attitude errors, using of radiation pressure to align the boom rather than gravity gradient.

When provisions are made for passive damping by thermally actuated tabs on the boom reflectors, operating when a disturbance displaces the reflectors from the penumbral shadow, any disturbance can be damped to 1% in 24 hours. No disturbances larger than 10 arc-seconds are anticipated after initial vehicle deployment and trim. Extensive analyses are found in Ref. 3.

Application to SCADM

The SAMPL space [illegible] provide mapping of active regions on an hourly basis with [illegible] resolution. Telemetry data rate limits the repetition rate. [illegible] incorporation of a spacecraft bubble memory system (on reliabi[illegible] [illegible]ents no image recorder was included in our original concept) would allow synchronized observations to be stored and transmitted later if the SCADM [illegible] required special, coordinated data collection.

The SAMPL space[illegible] be made more complex by adding other optical sensors [illegible] [illegible]ths, e.g., He 10,830A, UV or Zeeman triplet lines for polarization mapping of magnetic fields. It is not clear that a totally passive [illegible] [illegible]graph can be effected without introducing components with quest[illegible] [illegible]ility. A series of SAMPL spacecraft could add materially [illegible] three-dimensional character of the SCADM program. The [illegible] [illegible]ssure stabilization system might also be found attractive [illegible] [illegible] of a sun-referenced spacecraft at synchronous altitude [illegible] provide passive stabilization to a few arc minutes against the [illegible] [illegible]ient torque.

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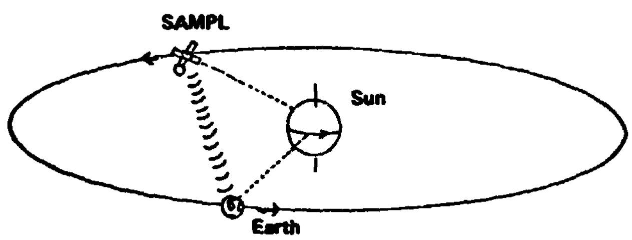

Figure 1A. SAMPL Mission Orbit Configuration

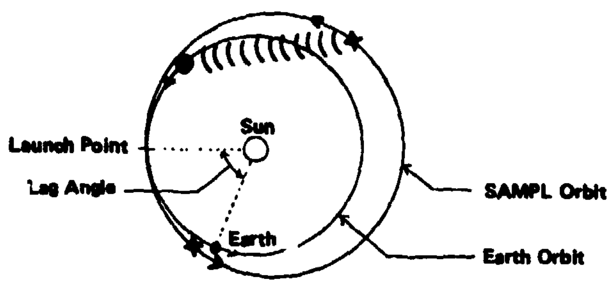

Figure 1B. Exterior Transfer Recommended for SAMPL Mission

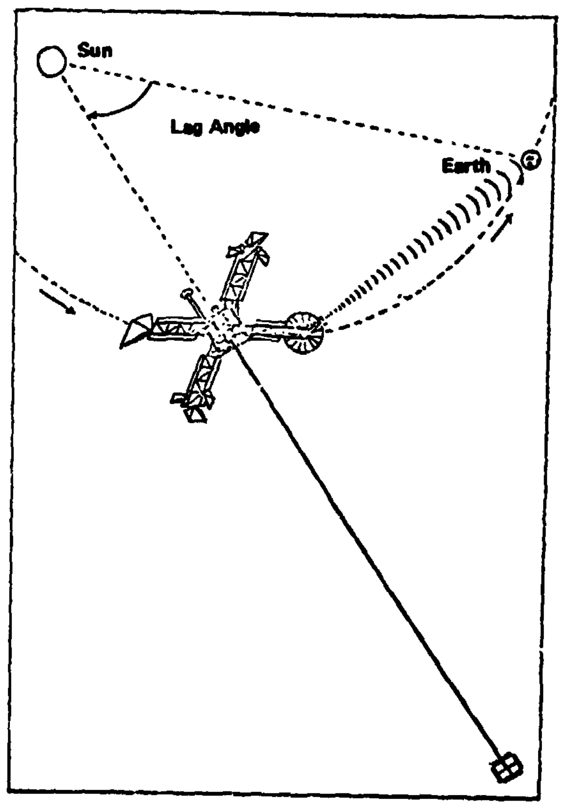

Figure 2. SAMPL Mission Communications Concept

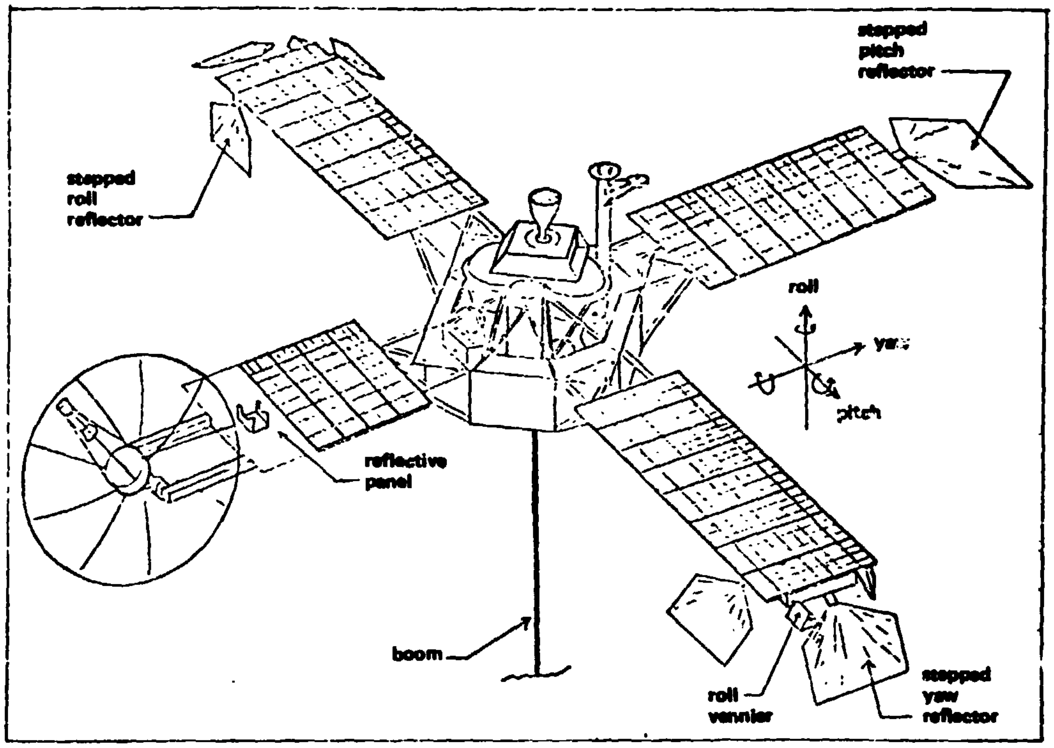

Figure 3A. SAMPL Spacecraft Body Detail Showing Locations of Trimming Reflectors for Radiation Pressure Balance

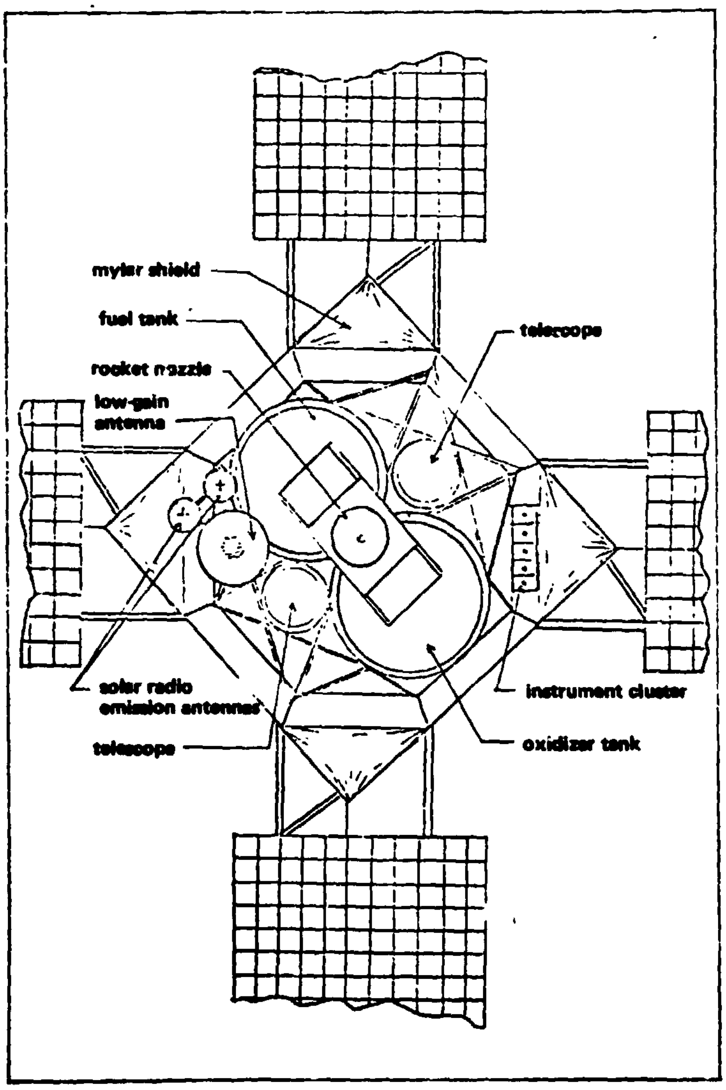

Figure 3B. SAMPL Spacecra t Main Body Detail Showing Locations of Principle Subsystems.

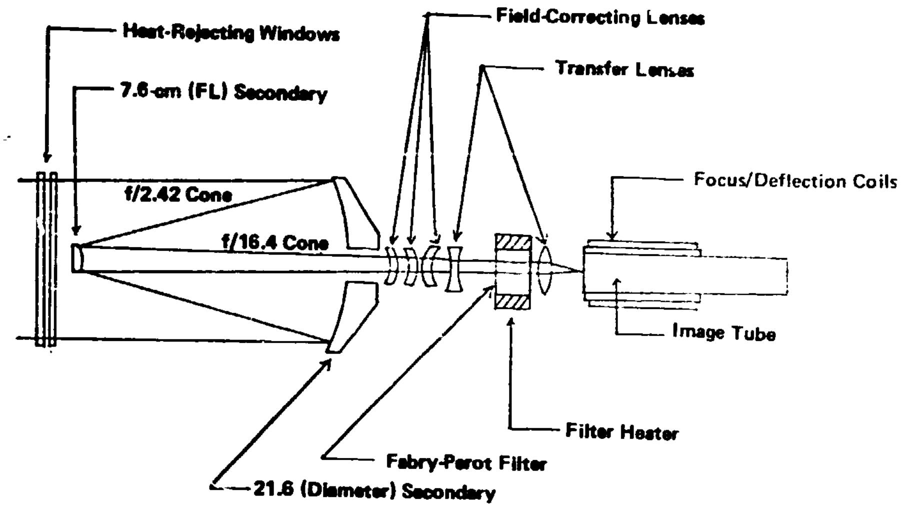

Figure 4. Image Dissector Video Sensor

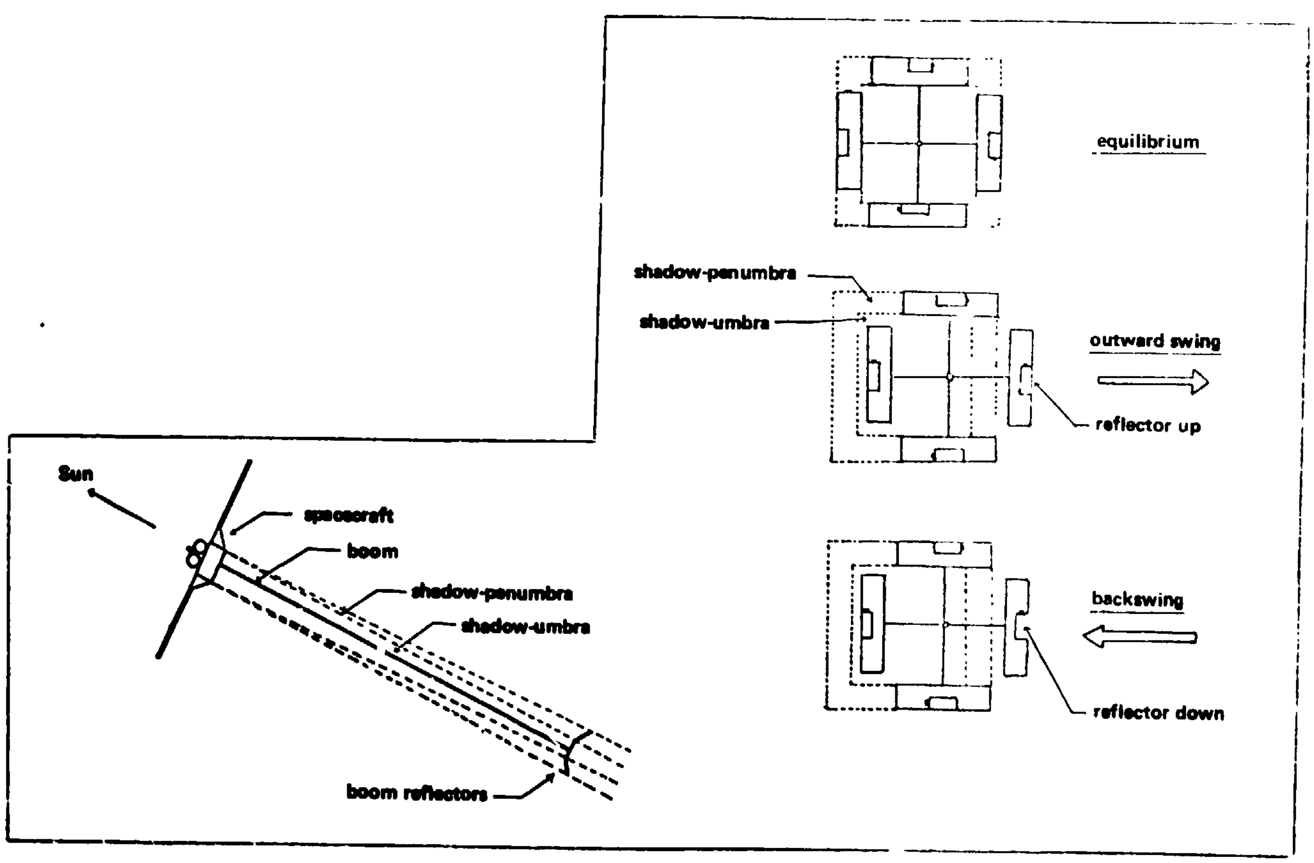

Figure 5. Passive Radiation Pressure Stabilizing Boom With Thermally-flexing Damping Reflectors. Boom Length: 33 meters.

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PROBLEMS OF INTERIOR STRUCTURE, THE SOLAR DYNAMO AND THE ROLE OF SCADM IN PROVIDING INTERIOR DIAGNOSTICS

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1. INTRODUCTION

The last ten years have seen an explosive increase in high-resolution observations of solar magnetic fields--from ground-based observatories and from space, in the visual, infra-red and X-ray ranges. Small scale magnetic fields, global oscillations, X-ray bright points and coronal holes have all been discovered. For the first time we are able to see the fine structure of magnetic fields at the surface of the sun and this tantalising wealth of information leaves me feeling that a decent understanding of solar magnetism can be attained within the next decade. Theory too has also made considerable advances, though it still lags behind the observations. As E. N. Parker has told us, "Nature is far more inventive than we are." Nevertheless, I remain optimistic. Turbulent behaviour is difficult to describe but I believe we shall discover how to pose questions that can be answered with sufficient precision to allow us to explain the weird behaviour of magnetic fields in the sun. It is reasonable to expect that the next ten to twenty years will produce an adequate theory of the solar cycle (which seems to me the principal problem of solar physics) and its relation to activity at the photosphere.

Dr. Noyes has already mentioned some aspects of our understanding of the sun' structure, of motion in its convective zone and of the solar cycle. In this review I shall attempt the difficult task of outlining what we know, what we do not know and what we would like to know. We naturally hope that SCADM will answer these last questions but I shall leave it to Dr. Brown to distinguish between those observations that are best made from the ground and those that must be made from space. In the time available I have necessarily to be selective in what I say; so I hope that nobody will be offended by omissions.

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2. SOLAR VARIABILITY

We seem to prefer to assume that the sun is immutable or if it varies, that the variations must be regular. Thus the variability of the solar cycle has only been accepted with reluctance. In fact one should expect the solar dynamo to oscillate irregularly; even simple nonlinear systems show aperiodic oscillations. characterized by the presence of "strange attractors" which are currently a fashionable topic for mathematicians to investigate. Looking back over sunspot numbers we can see a glitsch around 1800 and, of course. the Maunder minimum in the seventeenth century. The record can be extended by using anomalies in C^{14} abundance, which are correlated with the envelope of solar activity. The Maunder minimum, the Spörer minimum of the sixteenth century and the grand medieval maximum are typical of a pattern of behaviour that has prevailed for the last 7000 years and so. presumably, for most of the sun's lifetime on the main sequence.

There is increasing evidence for fluctuations in the solar luminosity. On a timescale of days. the old APO measurements show increases and decreases in the solar constant corresponding to the appearances of faculae and sunspots. Rocket and satellite observations suggest that the solar constant increases from sunspot minimum to sunspot maximum (though the surface temperature apparently goes down). Long term changes, associated for instance with the Maunder miminum, have been suggested as causes of climatic change on earth.

The sun's rate of rotation also varies slightly with the solar cycle and analysis of early observations indicates that differential rotation was much less during the Maunder minimum. Eddy has recently presented yet more striking evidence for solar variability: measurements of the sun's diameter made at Greenwich from 1840 to 1950 show a slow decrease at a rate of about 0.1% per century. Observations at the Naval Observatory in Washington show a similar shrinking in radius, which is consistent with discrepancies in the description of a sixteenth century eclipse. There may be some different explanation for these results, and the rate of change certainly could not have been maintained for thousands of years. Nevertheless, we must accept that, over its history, the sun may have varied far more than we would surmise from contemporary observations.

3. SOLAR STRUCTURE

For reasons of simplicity nearly all solar models are spherically symmetrical. These models are obtained numerically by evolving a model star of one solar mass from the zero age main sequence for 4.75×10^9 years and requiring that the present radius and luminosity be reached. Fortunately there are just enough parameters to provide a consistent result. In these models energy is generated by burning hydrogen to form helium (the p-p reaction) at the centre of the sun. This energy is carried outward by radiation for about 70% of the solar radius but the outer part of the sun convects. Current estimates place the base of the convective zone at a depth of about 200,000 km, where the temperature is 2×10^6K, but this depth is poorly determined.

There are some additional checks. Lithium, which burns at 2.4×10^6K, is largely depleted at the solar surface, though beryllium, which burns at 3.5×10^6K, is not. Thus the convective zone cannot be too deep, and must have beneath it a region with slow motions capable of providing some diffusion of Li and Be. In addition, there is the well-known neutrino problem: the lack of neutrinos shows that some part of the conventional picture is wrong, though it is hard to establish where the error lies.

The best prospect of improving our knowledge of solar structure comes from "solar seismology." Geophysicists have identified over one thousand normal modes of the earth, which are excited by earthquakes, and used their frequencies to determine the earth's internal structure. Similarly, the apparently irregular motion of the solar photosphere can be expressed in terms of the sun's normal modes of vibration. The 5-minute oscillations have indeed been shown to be global pulsations, corresponding to acoustic (or nonradial p) modes. Deubner's observations have established the structure of these modes in the K-ω plane (where horizontal wavenumber is plotted against angular frequency) and distinguished between modes with differing numbers of radial nodes. The amplitude of a node peaks at a particular depth (roughly where ω/K is equal to the local sound velocity) and so the modes can be used to probe the sun's internal structure. Deubner, Ulrich and Rhodes have found excellent agreement between the observations and predicted values for a solar model. More refined observations will yield more precise information about the structure of the convective zone.

Longer period solar oscillations have also been reported, though they are more controversial. Periods up to about 60 minutes (which is the period of the fundamental p mode) have been detected by the SCLERA experiment and Hill has recently shown that phase is maintained for many days. A persistent oscillation with a period of 160 minutes was discovered at the Crimean Observatory and confirmed by groups from Birmingham and Stanford. The precise nature of these modes is unclear but they seem likely to be g-modes (corresponding to gravity or inertial waves). If their spatial variation were established such modes could provide valuable information on the structure of the sun's deep interior.

4. VELOCITY PATTERNS

The solar dynamo depends on the complex interaction between motion and magnetic fields, so a description of the velocity is a necessary preliminary to any understanding of the dynamo. Let me first summarize the observations of rotation and of convective motion. Rotation can be observed by Doppler shifts for photospheric plasma or by following surface tracers. The rate of rotation of magnetic features increases with their size: Sunspots rotate faster than photospheric gas and coronal holes rotate faster than the sunspots. A more precise method of probing subsurface rotation is to utilise the rotational splitting of normal modes. This splitting corresponds to the fact that each mode is localised at some depth (as described above) and reflects the angular velocity at that depth. If the oscillations are resolved into eastward and westward propagating waves, the slight difference in frequency between these waves reflects the variation in angular velocity with depth. Deubner et al. find that the angular velocity increases down to about 15000 km depth but better observations are needed to improve on this result.

At the photosphere we see two discrete scales of cellular convection, the granules (with a diameter of about 1500 km) and supergranules (with diameters of 30000 km). The interactions of magnetic fields with these patterns of motion can be directly observed. There is much evidence, principally from Mt. Wilson, suggesting the presence of larger scale patterns with velocities of order 10 m s^{-1} and length scales of several hundred thousand kilometres. It is, however, difficult to provide definite proof that such giant cells exist.

Theoretical studies of convection and rotation have made great strides forward recently, largely owing to the simulation of hydrodynamic flows on big computers. It is easy to explain the presence of granules in a boundary layer where all scale heights are small and the ionization of hydrogen takes place. Yet there is still no adequate explanation for the existence of supergranules. On the other hand, all studies indicate that there should be large-scale, energy-carrying convective cells that extend through the full depth of the convective zone, with a characteristic time-scale of the order of a month.

The effect of rotation on these cells has received much attention. The prevailing opinion is that in the equatorial regions cells should be roll-like with axes parallel to the rotation axis of the sun. The existence of such rolls has been demonstrated, both theoretically and experimentally, by Busse. Whether this "cartridge-belt" pattern has been observed in the sun is much more dubious.

Nonlinear convection in a Boussinesq fluid, confined between two rotating spherical shells, has been studied by Gilman in a series of numerical experiments. There is a tendency to form elongated cells in these computations, and the sun's equatorial acceleration can be reproduced. However, the effect of turbulence in mixing angular momentum and angular velocity remains uncertain. Moreover, compressible convection has yet to be properly investigated.

5. MAGNETIC FIELDS

The range of fields observed in the sun has advanced considerably since the time of Hale. As well as sunspots there are active regions and complexes of activity. As resolution has improved smaller and smaller features have been discovered. Over all this range it seems that flux emerging from the photosphere is concentrated into discrete tubes (or ropes) and there is as yet no evidence for the existence of a weaker background field.

Active regions are the best known magnetic features. Their systematic behaviour (emergence in sunspot zones that migrate towards the equator, opposite polarity in northern and southern hemispheres, reversing every 11 years) defines the solar cycle. Outside active regions, almost all the magnetic flux is contained in the network, which outlines the boundaries of supergranules. When viewed with sufficient resolution, the network itself is composed of small flux concentrations (typically around 3×10^{17} mx, where a maxwell is the unit of magnetic flux and $1 \text{ mx} = 10^{-4}$ Wb). These small scale fields are typically intergranular and make up the filigree which can be observed from the ground only when seeing conditions are exceptionally good.

The above refers only to the instantaneous field configuration. It is important also to follow the emergence of flux through the photosphere and into the corona. Here again there is apparently a continuous spectrum, from active regions (10^{22} mx) down to the limits that can be seen. Smaller concentrations of flux, called ephemeral active regions (EARs), are seen in magnetograms but it is difficult to identify them unambiguously without synoptic coverage. Soft X-ray observations provide a less subjective means of noting flux as it emerges, for the expanding field lines produce enhanced X-ray emission from the corona. These X-ray bright points (XBP) were systematically observed from Skylab and have substantially enhanced our understanding of magnetic fields in the sun. The spectrum of emerging flux peaks towards small scales (the rate of emergence is greatest at 10^{19} mx, the limit set by resolution) and more flux emerges on small scales than as active regions. The Harvard/AS and E group finds XBP at all latitudes, with a greater concentration at the equator. Moreover the rate of emergence of flux (as shown by XBP) is greatest at sunspot minimum, as Dr. Davis will explain. The Skylab period included a single event, over the whole solar surface, with XBP associated with the emergence of vigorous activity (this will be described by Dr. Golub). Although magnetograms are essential for any study of solar magnetic fields, soft X-ray images provide important extra information.

Finally, we have learnt more about large-scale fields since 1970. Decaying active regions can form large unipolar regions. Within these regions some field lines are open, extending into interplanetary space. Coronal holes are found to coincide with open field lines, and their relation to interplanetary fields has been intensively studied. In particular, Levine has shown that the magnetic sector pattern can be derived from the large scale structure of smoothed-out photospheric fields.

6. DYNAMO THEORY

Despite some attempts to revive the oscillator theory, it is generally agreed that the solar cycle must be driven by a hydromagnetic dynamo in the convection zone. The basic concept of the dynamo has not changed since Parker's original paper. An initial poloidal field is drawn out azimuthally by differential rotation (so producing the field that erupts in active regions). This process is easy to grasp; the next stage, producing a reversed poloidal field from the azimuthal flux, is more subtle. Parker proposed that this be effected by cyclonic eddies with a preferred sense of helicity. Since then, the developments of mean field electrodynamics has yielded a variety of so-called $\alpha\omega$ dynamos based on the combination of helicity (the α-effect) with differential rotation. These models reproduce the main features of the solar cycle: the formation of strong toroidal fields that migrate towards the equator and then reverse for the latter half of the cycle. With suitable timing, a plausible butterfly diagram can generally be obtained.

The success of these kinematic models, where the velocities are prescribed, has led to some exaggerated claims. The fully magnetohydrodynamic dynamo problem, including the forces exerted by the fields themselves, is much more difficult and work on it has only just begun. Within the last few months Gilman has included magnetic fields in his numerical experiments and obtained dynamo action--but the details are very different from those envisaged in mean field electrodynamics. That theory relies on approximations which cannot be justified for motion in the sun; so the results, though qualitatively valuable, are not reliable in detail.

Theoretical studies of vigorous convection in a magnetic field show that magnetic flux ends up confined to ropes at the boundaries of convection cells and this result accords with the discrete flux ropes found at the surface of the sun. Any accurate treatment of the solar dynamo therefore involves the interaction between these flux ropes and the convective motion. This poses a formidable theoretical problem, where observations can offer valuable guidance.

An alternative picture of the solar dynamo is that the main effects occur at the base of the convective zone, where convection is less vigorous and the fields can be more diffuse. There the interaction depends critically on the effects of magnetic buoyancy, which has not yet been incorporated in any nonlinear calculation. From the theoretician's point of view, the dynamo problem remains as difficult as ever. We need guidance from observations, as well as access to Crays and other large computers. Still, I am confident that the problem can eventually be cracked.

7. WHAT WE NEED TO KNOW

The observations we need are listed below. Some of these may be made from the ground but many, as Dr. Brown will show, can only be obtained from space.

Global properties: The solar luminosity ($L_\odot$) and radius ($R_\odot$) must be measured precisely, so that variations of order 10^{-3} $L_\odot$ over a period of 11 years can be detected. Experimental checks on the apparent shrinking of the solar radius are also needed.

Oscillations (p and g modes): Precise measurements are needed for periods from 1 minute to at least 160 minutes. We need enough precision to resolve individual modes of the 5-minute oscillations and to confirm (hopefully) the reality of the long period oscillations. For the latter it is also essential to establish spatial structure so that the modes can be properly identified.

Velocities: Variation of rotation with time can be observed directly; variation with depth must be derived from the 5-minute oscillations. Large scale meridional circulations (reported by Beckers) and patterns corresponding to giant cells require observations with an accuracy of at least 10 m s^{-1}, extending over several months.

Magnetic fields: The fields in active regions and the network must be mapped in detail and related to the patterns of large scale motion. (For this purpose it is not necessary to resolve the fine structure of intergranular fields.) This requires synoptic coverage from magnetograms. At the same time, X-ray observations are needed to detect emerging flux and large scale structures.

In summary, continuous observations with sufficiently high resolution are needed in order to reveal the relationship between magnetic and convective structures. Such a program requires a combination of ground-based observations with others made from space. This overall program should cover a whole 11-year cycle. In particular, it is important to be ready by sunspot minimum (not later than 1985). Experience from Skylab shows that much more can be learnt when fields are relatively simple--for instance, the famous coronal hole could never have appeared at sunspot maximum. Further, the Skylab period covered a unique event which lasted for six months. In order to establish whether this behaviour is typical it would be necessary to maintain magnetograph and X-ray observations for about two years.

So we need to have a grand collaborative program. Theoreticians and observers must work together to define objectives and understand results. Careful planning is needed to isolate those observations that must be made from space with SCADM. Moreover, a sustained commitment from the whole solar physics community is needed to ensure success. I believe that the scientific gains would amply justify this effort and I hope it will be made.

QUESTIONS AND COMMENTS

COMMENT BY: J. H. Thomas, University of Rochester

DIRECTED TO: N. Weiss

You mentioned the importance of possible variations of the Sun's radius. In addition to the long-term decrease in solar radius discussed by Jack Eddy, there is the possibility of a cyclic change in solar radius over the solar cycle which I discussed in my paper yesterday (session on Solar and Stellar Variability - see abstract in these proceedings). SCADM offers an excellent opportunity to determine whether such a variation of radius with solar cycle does occur. Ground-based measurements of the absolute solar diameter are plagued by differential refraction, seasonal variations, and other atmospheric effects; thus, space measurements are particularly desirable. The solar luminosity, radius, and surface temperature are intimately related; it seems to me we need to monitor all three quantities to understand solar variability.

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X-RAY BRIGHT POINTS AND THE SOLAR CYCLE DEPENDENCE OF EMERGING MAGNETIC FLUX

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ABSTRACT

Soft X-ray imaging of the solar corona during the period 1970 to 1978 has resulted in significant modifications to our view of the solar cycle with respect to both the properties of the large scale (coronal holes) and small scale (X-ray Bright Points) solar magnetic field. In the latter case the particular contribution is to the emerging magnetic flux. Sounding rocket observations combined with the Skylab data indicate that the XBP are anticorrelated with sunspot number and are the dominant contributors to the total emerging flux spectrum during all but the maximum phase of the solar cycle. A continuous data set covering a complete cycle would enable the validity of this result, which has serious implications for the nature of the solar dynamo, to be confirmed.

1.0 INTRODUCTION

Since the early sixties NASA has supported a program of high spatial resolution solar X-ray astronomy at AS&E. One of the prime objectives of this program has been the study of both the large and small scale variations occurring in the corona during the 11-year solar cycle. The studies have used the data from sounding rocket flights and Skylab; the latter providing a major contribution by establishing a baseline against which the sounding rocket observations can be compared.

During the first decade of the program major advances were made in the fabrication of the X-ray optics, in the preparation of the broadband filters used to select the various soft X-ray wavelength ranges and in the development of suitable photographic emulsions which are used as the recording medium. These three areas of development had all reached fruition by 1970 and produced for the first time the high quality X-ray images to which we have now grown accustomed. A panoramic representation of these data is shown in Figure 1 where images from 6 rocket flights and 3 representative Skylab photographs are combined. The images cover the period 1970 to 1973 and show all the phases of the solar cycle except solar maximum, for which period no images of comparable quality exist. The combination of high resolution and sensitivity has revealed many new phenomena of which two have a direct bearing on the cyclical behavior of the solar magnetic field. The unique contribution of the X-ray images has been to clearly and unambiguously identify phenomena whose signatures, although present in the records of the photospheric magnetic field, tend to be obscured by a wealth of confusing detail.

2. CORONAL HOLES AND X-RAY BRIGHT POINTS

Historically the first major result of the program was the unambiguous identification of coronal holes followed by the recognition that equatorial coronal holes were the elusive 'M-Regions' which give rise to geomagnetic storms by their influence on the velocity pattern of the solar wind. Although coronal holes had been tentatively identified earlier on the basis of ground-based observations (Waldmeier, 1957) and low resolution X-ray pinhole and XUV heliograms (Russell and Pounds, 1966; Austin et al., 1967), they attracted little interest primarily because they were not clearly defined entities. However, three different groups reintroduced the subject almost simultaneously (Altschuler et al., 1972; Munro and Withbroe, 1972; Krieger et al., 1973) just prior to Skylab. The subsequent high resolution X-ray images obtained during Skylab ignited a general interest in the study of these indicators of the large scale structure of the solar magnetic field. Several categories, based on their heliographic location, are known each having a characteristic relationship to the solar cycle; for instance, the recurrent equatorial holes are present only during the declining phase of the solar cycle, while the polar holes are always present except perhaps during solar maximum. Although coronal holes can now be identified from ground-based observations, notably the He 10830 line, the reconfiguration of the magnetic field which occurs as their boundaries expand or recede is best studied with X-ray or XUV observations.

The X-ray observations have also shed light on the small scale structure of the magnetic field following the observation and classification of the features known as X-ray Bright Points (XBP). XBPs are small, compact, short-lived, magnetically bipolar regions whose size and lifetime spectra blend into the corresponding active region spectra.

Their major significance results from their identification as sources of emerging magnetic flux. The relationship of XBPs to the general solar field is still not understood. However what is clear is that the emerging magnetic flux associated with XBPs differs radically from that associated with active regions in at least two ways. The first, discovered from the Skylab observations, is that the XBP are distributed more or less uniformly over the solar surface in sharp contrast to the active regions which are limited to the equatorial band (Golub et al., 1974, 1975). The observations do suggest that there are two components to the bright point distribution, one associated with the active region latitudes and the second uniformly distributed over the entire disk.

The second difference is their variation with the solar cycle which appears to run counter to the well-known sunspot cycle.

3. THE SOLAR CYCLE VARIATION

A basic limitation of the Skylab study was that it covered only a short period (8 months) of the solar cycle and consequently the conclusions drawn from this period may not be typical of solar conditions throughout the 11-year cycle. To augment these data, four sounding rockets have been flown since Skylab and in particular two flights were made in September and November 1976 close to solar minimum. On both these occasions the X-ray images revealed that the corona was composed of low-lying weakly emitting structures, interspersed with very large numbers of XBPs. Coronal holes were visible at both poles, however, there was no evidence of the large equatorial holes which were so characteristic of the declining phase.

The most obvious and striking difference was the large number of XBPs. In order to compare their number with those from the Skylab period, the relative efficiencies of the two rocket telescopes were evaluated and compared to the Skylab telescope. Using these ratios the closest comparable rocket exposures were selected and were used to establish the bright point counts.

The major result of the investigation is shown in Figure 2 where the relative numbers of XBP in 1973 and 1976 are compared (Davis et al., 1977). The 124 daily averages from 1973 are plotted in the form of a histogram showing the frequency of occurrence of each number count. The histogram approximates to a Gaussian distribution, eventhough there were persistent non-random variations during the eight rotations observed, and the mean (39) and its standard deviation ($\pm$ 3) have been used to characterize the distribution. The values observed in 1976 are indicated by arrows and lie well outside the range of values recorded in 1973.

After scaling the 1976 values are [illegible] $\pm$ 8 and 75 $\pm$ 9. They are both consistent with a substantial increase in the number of bright points occurring between 1973 and 1976. In fact the average of the two 1976 observations, 83, is 110 percent higher than the combined average, 39, of the 1973 data. Under the assumption that the data from both 1973 and 1976 belongs to the same Gaussian frequency distribution, the probability that two random observations will result in the 1976 value is found to be 1 in 5×10^6. Even using the lower bounds for the 1976 observations, thus maximizing the probability, the chance of making the observations is still only 1 in 2×10^5. We realize that because of deviations from a Gaussian distribution these probabilities are not strictly true but even so the inescapable conclusion remains that the 1976 data belong to a different frequency distribution with a higher mean value.

In Figure 3 we show the latitude distribution of XBP seen on the two 1976 images, compared with the 1973 average. The 1976 data show much larger error bars since only two photographs were available. However, it is clear from the figure that there were more XBP at <u>all latitudes</u> in 1976 than in 1973, with the possible exception of the extreme polar latitudes where the statistical sample is small. Thus it is clear that the emergence of small-scale magnetic flux regions at solar minimum does not follow the pattern set by the larger active regions. Unfortunately, further details of the behavior within restricted latitude intervals cannot be deduced because of the limited statistics of the data sample.

The increase in the number of XBP is even more significant when compared to the changes in the other indices of solar activity between 1973 and 1976. For instance the average relative sunspot number, R_z, for the Skylab period, May to November 1973, was 35 whereas the index for January to December 1976 averaged 13. Thus while the sunspot number has <u>declined</u> by a factor of 3, the number of XBPs has <u>increased</u> by over a factor of 2. The implication of this result is that XBPs vary out of phase with the solar cycle as measured by the usual indicators of activity.

To explore this possibility further we have reexamined data from the older rocket flights going back to 1970 and the two other post-Skylab flights. Following a careful calibration program to compensate for the instrumental differences, a consistent pattern of anticorrelation between sunspot number and bright point count is found. The data are summarized in Figure 4 where we show the variation with time of R_z and XBP number, both normalized to maximum values of 100, over the last sunspot cycle. It is apparent that the variation in XBP count is close to 180° out of phase with R_z. This demonstrates that XBP must represent magnetic flux which emerges independently of the active regions. For if the emergence of XBPs was somehow associated with the emergence of the larger active regions (e.g., if the XBP represented either precursors or remnants of the larger active regions), then the bright point count could not lead or lag R_z by much more than the characteristic lifetime of the flux associated with the active regions (~ 6 months). Instead the observed phase lag is closer to 6 years. Therefore, in order to determine the total magnetic flux emerging at the solar surface at any time, it is necessary to sum the magnetic flux represented by the XBPs with that represented by the active regions.

4. IMPROTANCE OF THE RESULT

The last conclusion, that in order to determine the total magnetic flux emerging from the solar surface, it is necessary to sum both the XBP and active region components, provides the significance to the observations. For now, the possibility exists that the amount of magnetic flux emerging throughout the cycle is constant or even that the total increases at solar minimum.

Comparison of the X-ray data with high resolution magnetograms shows that on average XBP emerge with $2-3 \times 10^{19}$ Mx of flux (Harvey et al., 1975; Golub et al., 1977). Although this is more than an order of magnitude less than for active regions, because of their large number, XBP contributed 80 percent of the total of all emerging magnetic flux at the time of the Skylab observations. Under the assumptions that the XBPs seen in all of the rocket flights are physically the same so that the characteristic value of 3×10^{19} M_x per bright point can be used for all the data, and that the sunspot index R_z may be used as a relative indicator of the amount of flux emerging in the form of active regions throughout the solar cycle, it is possible to proceed to estimate the relative contributions of XBP and active regions to the total magnetic flux spectrum of the sun during the period 1970 to 1978. By taking the 1973 fraction of 80 percent as a base, we estimate that ~ 40 percent of the total magnetic flux in 1970 emerged in the form of XBP. The contribution of XBPs to the total reached a peak of ~ 95 percent in 1976 and has since declined to about 70 percent in early 1978. From this analysis we conclude that XBPs make a substantial contribution to the total emerging magnetic flux spectrum throughout the entire solar cycle and are the dominant contributors throughout the declining, minimum and ascending phases.

5. CONCLUSIONS

High resolution X-ray images of the solar corona contribute to the study of the solar magnetic field by revealing, in a unique manner, the topology of the extension of that field into the corona. It is extremely difficult, if not impossible, to obtain this information in other ways, for instance by extrapolating the measurements of the photospheric magnetic field because this requires theoretical modelling, e.g., potential field calculations, which results in, at best, an approximation to the real situation.

The X-ray images, although recorded only during brief intervals over the last decade, have revealed two new facets of the behavior of the solar magnetic field which must be explained in any comprehensive theory of its origin and variability. In particular it has been learned that XBPs represent a dominant feature of the emerging magnetic flux spectrum through the majority of the solar cycle. In fact they display a counter cycle to the better known sunspot cycle and at this time the relative importance of the two cycles to the actual description of the solar dynamo is not known. Because of the limited number of data samples, the statistics of the observations over a solar cycle are not high and other contributions of XBPs to the complete picture of the solar magnetic field almost certainly remain to be discovered. An example is their latitude distribution which is known to differ markedly from that of active regions but whose possible cyclical variation is completely unknown.

In this context the SCADM mission presents a unique and valuable opportunity to obtain an uninterrupted, long duration sample of coronal observations. In the recording of these data, the value of high sensitivity, high resolution observations cannot be overemphasized. For although both XBPs and coronal holes are visible, in retrospect, in the X-ray images made prior to 1970 their importance was not realized at the time because the lack of definition in the observations did not allow a positive and unambiguous identification to be made. Since the coronal observations will still be to some extent exploratory, the preliminary planning for the SCADM spacecraft must reflect the requirement for imaging data with comparable quality to those of current rocket programs.

ACKNOWLEDGMENTS

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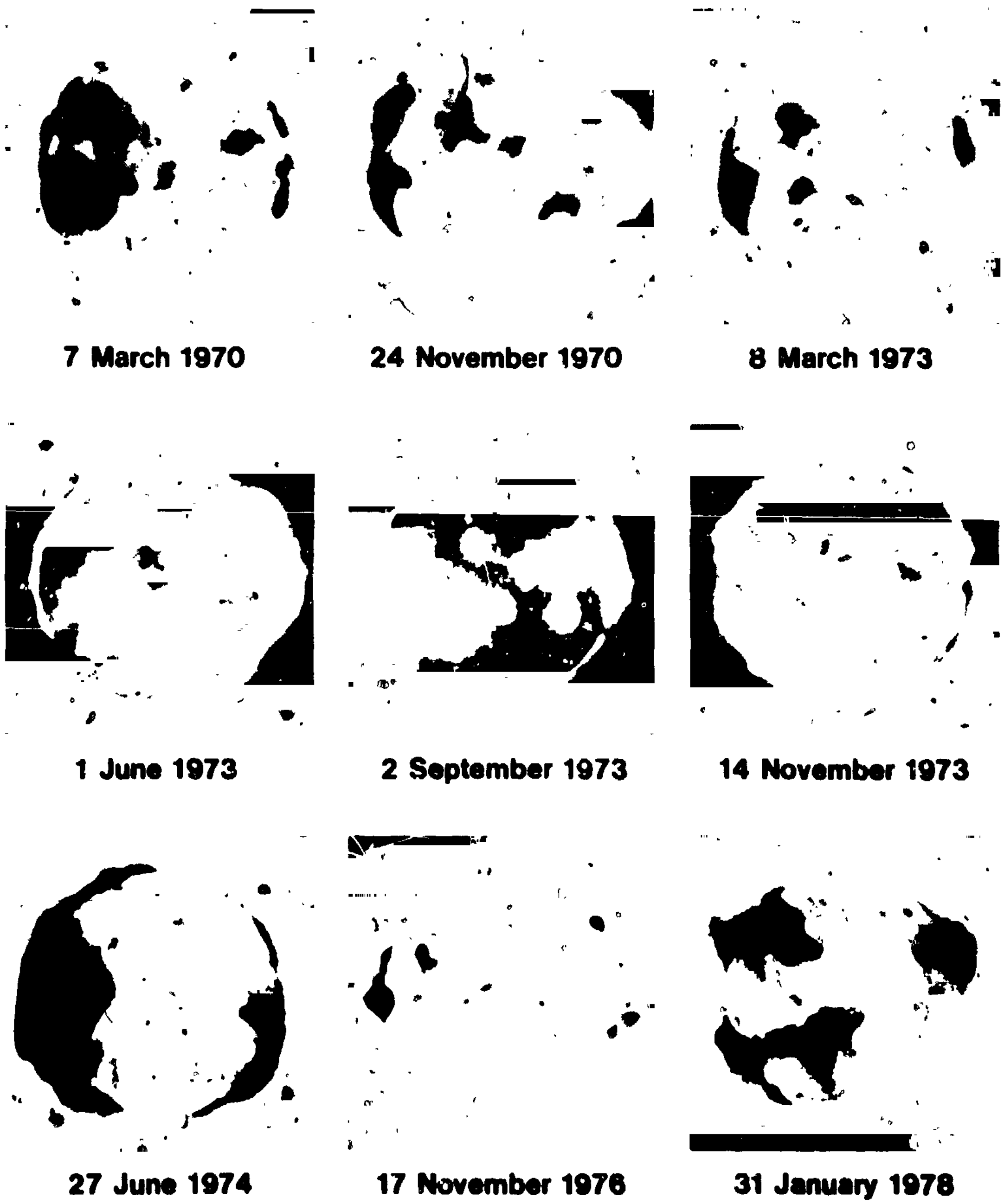

Figure 1. Coronal X-ray observations during the period 1970-1978. A collection of images from sounding rockets and Skylab.

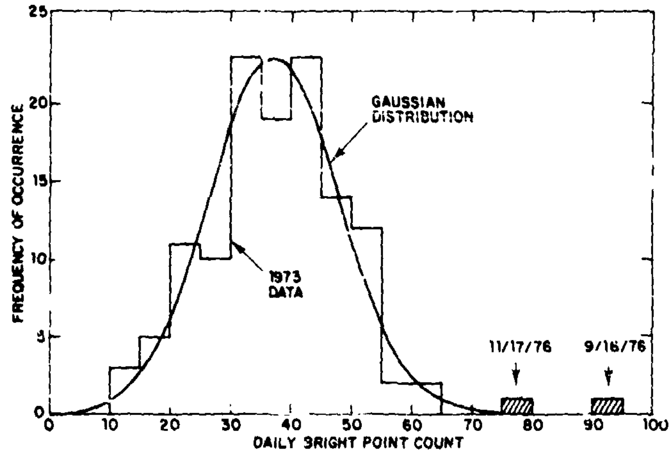

Figure 2. Daily X-ray bright point counts. The curve is a Gaussian distribution fitted to the 1973 data.

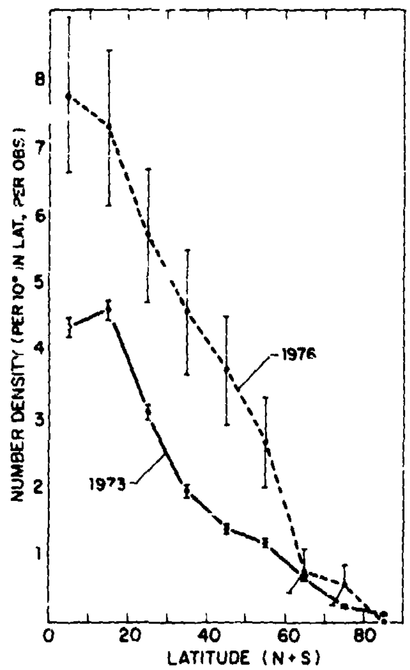

Figure 3. The latitude distribution of X-ray bright points in 1973 and 1976.

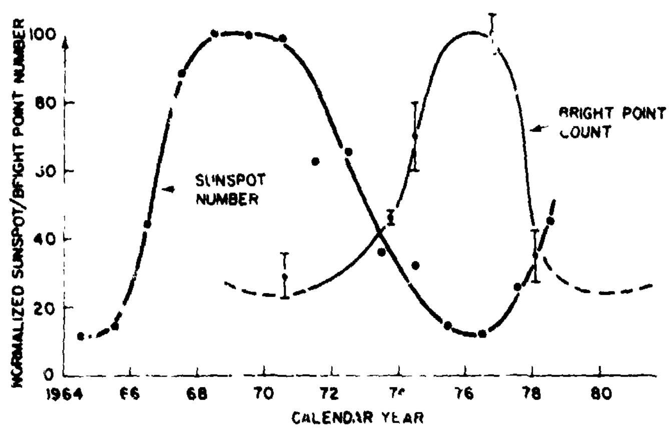

Figure 4. Variation of the number of X-ray bright points with the solar cycle.

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X-RAY BRIGHT POINTS AND THE SOLAR CYCLE

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Abstract

Soft X-ray filtergrams show the presence on the Sun of numerous small, closed regions of coronal emission. These features, called "X-ray bright points" correspond to topologically closed short-lived regions of emerging magnetic flux. As a function of size or lifetime they form a broad spectrum of activity which is continuous with the active regions. The shape of the Sun's activity spectrum is such that the majority of all magnetic flux emerging at the surface comes in the form of bright points, i.e., regions living less than two days.

Examination of soft X-ray data obtained from 1970 to 1978 shows that the number of bright points appears to be anticorrelated with traditional activity indices, such as sunspot number; the anticorrelation persists after corrections are made for obscuration by active regions. Comparison of X-ray data with KPNO magnetograms shows that to within a factor of two, the average total amount of magnetic flux emerging over the full Sun is constant through the entire period of observation. The Solar cycle therefore appears to be more an oscillation in the wavenumber distribution of emerging flux than of the total quantity of magnetic flux produced.

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1. Introduction

High spatial resolution observations of the Solar corona in its characteristic radiation, soft X-rays, have proven to be a valuable new tool in the study of Solar activity and active regions. For a number of reasons (cf. Vaiana et al., 1973), soft X-ray instruments provide extremely high contrast between closed and open magnetic field regions in the Solar atmosphere, so that the X-ray emitting plasma observed by imaging instruments belong primarily to the closed corona. The corona is observed to be highly structured and recent theoretical work has shown the advantage of considering the corona to be fundamentally inhomogeneous, with loops forming the relatively isolated building blocks (cf. Vaiana and Rosner, 1978).

The sharp division in X-ray brightness between open and closed regions is particularly advantageous in studying the small-scale end of the active region distribution, i.e., the X-ray bright points or XBP. This name was given to the numerous small regions of bright X-ray emission which were seen on early high-resolution images (Vaiana et al., 1970). Now what is significant about these small features is that most of the magnetic flux emerging through the Solar photosphere comes up in regions living two days or less. Moreover, detailed study reveals major variations in magnetic flux emergence at locations on the Sun for which flux emergence had not heretofore been considered and with spatial and temporal scales which have not until now been observed. Finally, there is evidence from observations over most of a Solar cycle that the total amount of magnetic flux integrated over all emerging scale sizes may vary little, if at all, through the Solar cycle.

Over the past decade we have begun to form a comprehensive picture of the small-scale end of the Solar magnetic flux emergence spectrum, with profound implications for Solar cycle and dynamo theories. We will first present the results from Skylab in §2, more recent findings in §3 and discuss the implications and directions for further research in §4.

2. Results from Skylab

Bright points had been observed in several rocket flights before the launch of Skylab and many of their basic properties had been established. Physical parameters such as size, electron temperature and density were known and we were reasonably certain that they represented magnetically bipolar features.

However, the availability of continued observations over many hours and days in the Skylab data provided a new dimension for the analysis. We were able to study the lifetimes and evolution of activity on all time scales and to look for large-scale patterns in emergence on the Solar surface. The motivation, of course, was to find out whether XBP represented emerging magnetic flux and if so, how much of it and what ney information could be gained about Solar magnetic activity from studying these objects.

By comparing the X-ray data with high-resolution KPNO magnetograms we were able to establish that (Golub et al. 1977):

i) XBP represent emerging magnetic flux and they are bipolar;

ii) the lifetime in X-rays of XBP is (to first order) linearly correlated with the total magnetic flux in the region;

iii) the relation between lifetime and Φ_{Tot} extends over three orders of magnitude, the proportionality constant being $\sim 10^{20}$ Mx/day.

For the Skylab observing period the relative contribution of bright points to that of active regions, using two-day lifetime as a demarcation between the two classes, has an average value of 4 to 1. In other words, features living less than two days (but more than two hours) contributed about 80% of the total emerging Solar magnetic flux.

Because bright points in a sense represent the "whole story" of magnetic flux emergence on the Sun, we need to examine the global properties of their emergence. Theoretical models of the Solar dynamo and of the cycle could potentially contain enormous systematic errors if the short lifetime end of the activity distribution, which we have shown to contain the vast majority of all magnetic flux, emerges with substantially different properties from those of the large, long-lived active regions. In this regard we have at present only partial answers; these pages may be viewed as a progress report on work which is now being performed.

X-ray bright points have a broader latitude distribution than do longer-lived active regions (Golub et al. 1974), which is consistent with magnetograph and CaK observations of ephemeral regions (Harvey and Martin 1973). These results are in turn consistent with the well-known observation that pores (small sunspots lacking penumbrae) are more broadly distributed in latitude at a given phase in the cycle than are sunspots (Bray and Loughead 1964). It is apparent that emerging flux regions with pores represent intermediate cases between the shortest-lived bright points and the active regions. Born (1974) has identified such regions as living from 10 to 60 hours; shorter-lived regions do not develop pores and longer-lived ones develop penumbral spots. An association between lifetime and total magnetic flux, similar to the one we discussed above, was inferred.

More recently, we have found that there appear to be large-scale variations in bright point emergence. The variation appears to consist of a single event over the full Sun, correlated with an emergence of active regions. The total number of XBPs emerging per unit time varies globally by a factor of two over a time scale of 2 to 3 Solar rotations, and there is a local, temporary depletion of XBP near the large active regions. We are looking into the possibility that the observed variation is connected with the deep-rooted dynamo action in the Sun.

3. Solar Cycle Variation

Data obtained from two rocket flights in 1976 revealed a dramatic and unexpected change in the spectrum of Solar activity (Davis, Golub and Krieger, 1977). Whereas the number of large active regions had decreased substantially from 1973 to 1976, the number of bright points observed had increased significantly.

This result prompted a reexamination of other available data from two flights in 1970 and one in 1974; an additional flight in 1978 provided a further data point. Analysis of the six rocket flights plus the ATM data shows a consistent pattern of anticorrelation between the relative number of bright points and the level of activity as measured by the sunspot index.

With the above considerations, using the relative numbers of XBPs and active regions observed from 1970 to 1978 and taking the 1973 fraction of 80% as a base, we estimate that 40% of the total magnetic flux in 1970 emerged in the form of XBPs, and a peak of ∿ 95% in 1976. Early in 1979 the fraction was ∿ 70%, much the same as in 1973. We see that XBPs represent a substantial contribution to the total emerging flux spectrum throughout the entire solar cycle and are the dominant contributors through the declining, minimum, and rising phases.

During the <u>Skylab</u> period there were typically 1.5×10^3 XBPs emerging per day,† each with 3×10^{19} Mx of flux and active regions added another 20%. The typical value for magnetic flux emergence on the Sun is, therefore, $\gtrsim 5 \times 10^{22}$ Mx per day.

If we assume that the XBPs observed in all rocket flights are the same, then the total amount of magnetic flux emerging at solar minimum is twice as great as in 1973; the total in 1970, near maximum, is nearly identical to that in 1973. However, the shift toward smaller regions at minimum could extend down to features as small as XBPs, so that the larger number observed does not necessarily imply more total magnetic flux emerging. The possibility of a factor of 2 decrease in the average flux per XBP exists in the 1976 magnetogram data (J. Harvey, private communication) so that within the factor of 2 the average total amount of magnetic flux emerging on the Sun throughout the solar cycle is constant.

IV. Discussion

In this paper we have presented the results in decreasing order of certainty. A schematic outline of our knowledge may be portrayed as shown in table 1. It appears that the least certain results are those with the greatest potential significance.

The question of the Solar cycle variation is the one which we

† The number 1.5×10^3 per day is equivalent to 500 XBPs on the full Sun at any one time, or 250 on the visible disk; this number is clearly greater than the average of 38 quoted in the text. The smaller numbers, such as those quoted in table 1, are <u>relative</u> counts and are obtained from short exposure images, in order to minimize obscuration and visibility effects from overlying coronal structures. The larger numbers, used for obtaining flux estimates, are based on the scaling of XBP counts in coronal holes on long-exposure images (cf. Golub <u>et al</u>. 1974, figure 7).

presently feel to be the most important. Based on the behavior of the familiar large active regions, one would presumably expect that the short-lived regions and the bright points would have a similar Solar cycle variation. That is, the number of regions emerging per unit time or the integrated total quantity of emerging magnetic flux would be expected to vary roughly in phase with other activity indices, such as the sunspot index R_z. Another possibility which might have been observed would be no average variation in the number of bright points. One could then have argued that these features have no relation to the Solar cycle and represent some unrelated surface effect. The observed anticorrelation described in §III therefore argues not only for a close association between XBP and the Solar cycle, but for a possible major revision in Solar dynamo calculations.

Although the Solar cycle variability is the major unresolved question in bright point research, there are a number of other significant areas still to be explored. For example, there are no simultaneous magnetograph and soft X-ray observations having good time resolution. With such data one could determine unequivocally whether all bright points represent emerging magnetic flux and whether all detectable emerging flux shows up in X-ray emission. Such data could also be of use in answering far broader questions concerning the physical structure of the corona and its relation to the magnetic field.

Other areas of research which have been suggested and which are presently under study include: the relationship between bright point flares and macrospicules (and spicules), analysis of flare energy storage and release mechanisms using bright point flare data, and bright points as sources of the solar wind. Clearly, there is a great deal of work yet to be done.

Table 1. X-ray Bright Points and Solar Activity

	Property	Level of Certainty	Significance
1.	Bright points are magnetically bipolar closed regions.	Certain	They appear to be a little-explored form of Solar activity.
2.	Bright points form the short lifetime end of a continuous distribution of activity.	Well established	There are no "characteristic" parameters for active regions on the Sun.
3.	Bright points represent emerging magnetic flux.	Fairly well established	Magnetic flux is produced in a large range of scale sizes in the Sun.
4.	During the Skylab period most of the magnetic flux on the Sun emerged in the form of bright points.	Highly probable	The basic method of magnetic flux generation may be small, rather than large, concentrations.
5.	During most of the past Solar cycle, bright points dominated the emergence of magnetic flux on the Sun.	Appears likely	Dynamo theories for large active centers may be missing much of the true picture.
6.	Bright points vary in anticorrelation with long lived active regions throughout the Solar cycle.	Appears likely	The Solar cycle may be an oscillation in wavenumber of flux production rather than in total quantity of magnetic flux emerging.
7.	The total average rate of magnetic flux emergence on the Sun may not vary with the cycle.	Suggested by results to date	

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Observable Solar Features Which Provide Clues to the State of the Solar Dynamo

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Abstract. Space experiments are suggested to better monitor the solar dynamo and solar luminosity variations. Polar and other magnetic fields, sunspots, coronal holes, filaments and other observable solar and solar wind phenomena can provide us with important links to test and discover physical mechanisms which relate solar activity to terrestial weather, climate, and possibly population variations.

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This report discusses observations which may provide useful clues to the state of the solar dynamo for the purpose of predictions and understanding. What this author assumes, is the conventional understanding of the solar dynamo, after the descriptions and models of Babcock (1953), Leighton(1969), Parker (1977), and Howard(1977). The author realizes there are uncertainties in these ideas. For example, Leighton found a best fit with " the interior rotating faster than the exterior ", whereas other models only assume latitudinal differential rotation. The basics, however, are generally agreed upon.

The conventional dynamo transform the sun's poloidal field by differential rotation into a toroidal field; this toroidal field gives rise to subsequent spots and solar activity. After this, the poloidal field is regenerated with a reversed sign. McIntosh(1979) describes the work of Shove, Brown, Sargent III, Schatten et al.,and others to predict the solar activity cycle. Useful parameters and indices for prediction appear to be geomagnetic indices (aa,AE, H component), magnetic activity during the declining phase, occurence of " abnormally quiet days ", auroral activity, etc. Thus the geomagnetic field may serve as a test field to examine the solar dynamo. Here we concentrate on solar observations themselves. Among those that appear to relate fairly directly to the cycle by way of the Babcock dynamo theory are:

(1) magnitude of the solar polar magnetic field,

and

(2) latitude of sunspots, and other features.

I concentrate on the findings of Schatten et al. (1978) to predict solar activity from the magnitude of the sun's polar field, not because it appears more accurate than the geomagnetic methods, but because it is closely related to dynamo theory, and a report of his and his coauthors will be less likely misrepresented. In this method, the amplitude of a given cycle is partially (perhaps to a large extent) governed by the sun's polar field at solar minimum (the start of a cycle). Differential rotation may play a role in dynamo theory, but Schatten et al. find the amount of polar field variability from cycle to cycle (factors of 2 or 3) far exceeds the variability of the reported differential rotation.

Figure 1 shows four methods of obtaining the strength of the sun's polar magnetic field in past years (all indirect) near solar minimum (abscissa in each case) graphed against the following cycle's maximum yearly average sunspot number, R_m. The 1976 value predicted a value of 140±20 for cycle 21's yearly average maximum sunspot number. The relations shown by Figure 1 can be expressed mathematically as:

(1) $$\bar{R}_m \cong 110|B| \cong 20\angle \approx 4.5 \text{ P.F.B. angle},$$

where $\bar{R}_m$ is the mean maximum annual sunspot number, B, polar field strength in Gauss; $\angle$, the " flattening " of the interplanetary current sheet at 1 AU; and P.F.B. angle is a coronal measure of the angular flattening in the inner corona due to the sun's polar field (observed at eclipses).

Figure 2 shows the prediction superposed with sunspot monthly data (crosses); the 1978 yearly average (dot) shows good agreement. The duration of the cycle was not predicted and thus the fall-off of R_m in the 80's is not a test of the polar field strength method; the curve just suggests an average return to low levels of activity in the 80's.

It is useful to note that the latitude of solar features may be combined with Waldmeier's (1939) findings to give an indication of the progression of the spot cycle. For example, Figure 3 shows graphs of the mean latitude of spots (ordinate) vs. time (measured in solar rotations) from sunspot maximum. The 5 graphs refer to the maximum R_m of the cycle (as in Figures 1 and 2). This is basically Spoerer's relation. If we assume the previous prediction (or any other) is correct, for example, and say $R_m \approx 140$, we use the top curve. From the Geophysical and Solar data books, we find spot latitudes for May (Regions 1710 through 1745) are near 20° latitude. Thus Figure 3 would place May '79 about 11 rotations before sunspot maximum; thus, the cycle should peak near early 1980. The mean latitude of spot groups could be carefully monitored throughout the cycle, with the subsequent progress of solar activity using Waldmeier's relation as follows.

Let the relation be expressed analytically as:

$$(2) \qquad \bar{\Phi}_{m+x} = \left[8-6(x/50)+4(x/50)^2\right] + \left[7-2(x/50)-(x/50)^2\right] \cdot R_m/100$$

where $\bar{\Phi}$ is average spotgroup latitude; and x time from solar maximum, positive in the future. Now, given a $\bar{\Phi}$ and an R_m, values of x can be obtained by finding the solutions to the above quadratic equation. For the case in hand, the two solutions for May '79 mean sunspot latitude near 20°, are $x = -10.2$ rotations and $+91.6$ rotations. The first tells us we are before solar maximum — slightly under a year away; the latter is unphysical as it refers to the previous cycle, whose R_m we did not use. One may also get predictive information about the latter phases and the end of a cycle by " asking " equation (2) " When will the spots reach, say, 5° ? " and using such criteria as an estimate of a cycle's finish.

Filaments, coronal holes, and other coronal observations monitored from space and ground observations may further provide useful information about the solar cycle's progress. Figure 4 from Baumgardner(1979) shows a sample H. photo of the sun using the new Boston University solar laboratory. Polar coronal holes provide us with information about the reversal of the sun's dipole field. This reversal really marks " the beginning of the end " of a solar cycle, as subsequently, the cycle is running on stored subsurface toroidal magnetic field rather than regenerating new toroidal field from existing polar field. Thus the northern and southern polar filaments in Figure 4 show the polar cap field on the wane, further suggesting we are close to the peak in the solar cycle. Numerical studies similar to the previous analysis could make this more quantitative. Space experiments to accurately define locations, sizes, etc. of the polar coronal holes and filaments are direct clues to the workings of the cycle. Coronal features themselves can add to these understandings. (See Vaiana, et al.,1973, and Papagiannis and Wefer, 1978).

Other parameters, such as spots, pores, and bright points would give clues, if sufficient theoretical analyses were undertaken, as to their distribution of magnetic versus kinetic energy flux. For example, a simple monitoring of the umbra-penumbra ratio of spot groups may tell us about the relation of convective mixing energy. Some of the above parameters, however, do not relate in a clear way, to existing dynamo theories, and it is a challenge to the scientific community to uncover the deeper, in both senses of the word, meanings of our observations.

New areas for investigation are suggested by the pioneering work on the solar rotation by Howard and Harvey(   ) and Livingston and Duvall(1979). They report a secular variation to the differential rotation with the latter authors reporting an 11-year variation of the polar latitudes; this is associated with the solar cycle. Livingston and Duvall offer one explaination for the latter.

This is the solar polar wind drag effect applied preferentially near the times of solar minimum, when the polar regions are most open. Schatten's(1973) model may only explain part of the differential rotation (along with other theories) or perhaps the entire differential rotation. The above findings are, however, supportive that polar wind drag is occurring on the sun.

The secular variation of the general solar rotation may not be so easily explained. One possibility is a tie-in with the state of the dynamo. This can be further studied by examining the historical records recently uncovered by Herr(1978) and Eddy etal.(1977) during the time of the Maunder Minimum.

The solar rotation during that epoch, in the 17th century, was found by measurements and calculations of the sunspot drawings of Harriot, Scheiner, and Hevelius. These findings show an increased differential rotation of the lower sunspot latitudes with the inception of the Maunder Minimum. Thus a secular variation of the differential rotation was present then also. At first that finding is somewhat puzzling, as dynamo theory might suggest that a more rapid rotation of the lower latitudes would imply a greater field-winding capability and thus an increase in sunspot activity following this behavior, rather than the Maunder Minimum.

The resolution of the above dilemma is found by considering other solar parameters which are varying at the same time as the solar rotation during this past epoch and play a more important or overriding role in determining the level of solar activity. The previously referred to, polar field variability, is in recent times a factor of 2 or more, whereas even the Maunder Minimum rotational variations are less than 15 %.

If the polar field experienced a near cancellation prior to and during the Maunder Minimum, the cycle would continue at a low level (Link, 1978); however, with little energy going into the cycle, little drag on the differential rotation would be concomitant, resulting in a secular increase in the differential rotation, perhaps as reported.

The present secular variations cited by Livingston and Duvall and also reported by Howard(1978) may be a consequence of secular variations of the dynamo. Feynman and Crooker(1978) report long term variations in the geomagnetic (aa) index, which relates to the solar wind and sun, and thus is providing a clue to long-term secular variations on the sun and, particularly, the differential rotation and the state of the dynamo.

The relatively rapid (decade) variations observed in the differential rotation suggest a method of estimating the extent in depth of the region partaking in the solar dynamo variations. Equating a depletion of the power of the solar activity cycle of $\approx 10^{27}$ erg/s over a few decades with the energy associated with the reported variations of Herr(1978) and Eddy(1977), suggests the solar differential rotation (associated with solar activity) may not extend the full depth of the convective zone. The above calculation suggests a thickness of order 10^4 km rather than 10^5 km. It is important to note this estimate applies only to the variations.

Considering the relations of long term solar activity to terrestial weather suggested by the work of Mitchell et al. (1977), Siscoe (1978), and Dicke (1978) it is clear that observations of the solar dynamo (particularly from space) are the most important astronomical observations to mankind. Unless one believes in astrology, it is clear that solar variations are more important to mankind than other stellar phenomena. We hope future resources spent on science will reflect the practical as well as the esoteric nature of research.

Figure 5, for example, shows solar activity variations (after Eddy, 1977) deduced from ^{14}C dating deviations and world population variations from the data of McEvedy and Jones (1978) for the last two thousand years. The early data is subject to the greatest uncertainties, but apparent dips occur in the near 300-500 AD, the 15th, and the 16th centuries in both curves. Further, the population variations are not only in the centers of the most populated areas, but are more universal – seen globally in widely separated countries as well. The changes may be related to specific epidemics – Black death, for example; thus, the associations could be described as coincidental. Nevertheless, the underlying original cause of such outbreaks could be the climate related variations reported by Eddy. For example, the T and W curves show the mean temperature of England and the winter severity index for the Paris-London area.

The monitoring of solar activity and luminosity variations has been recommended by NOAA's International Solar-Terrestial Predictions Working Group on Sun-Weather/Climate research. Utilizing temperature sensitive photospheric lines or other techniques to monitor the solar luminosity would be a boon to such studies. Space experiments designed to examine the crucial sun-weather related parameters outlined would greatly aid these studies.

A recent report by Foukal(1979) suggests the 27-day luminosity variations could be as much as 0.7 %. Such structure on the sun relates to subsurface magnetic fields and/or velocity flows. Improved solar monitoring and theoretical interpretations of terrestial and space observations have a good chance of uncovering practical sun-weather relations. We must further be able to understand and predict the solar dynamo magnetic field to provide advance prediction of any sun-weather relation uncovered.

To conclude, observations of the sun appear to be the most relevant astronomical observations to mankind. We know that the earth's atmosphere is a hindrance to many of these observations, and suggest the major weakness in sun-weather/climate studies is the poor observations of crucial solar and terrestial parameters relevant to these studies.

Acknowledgements.

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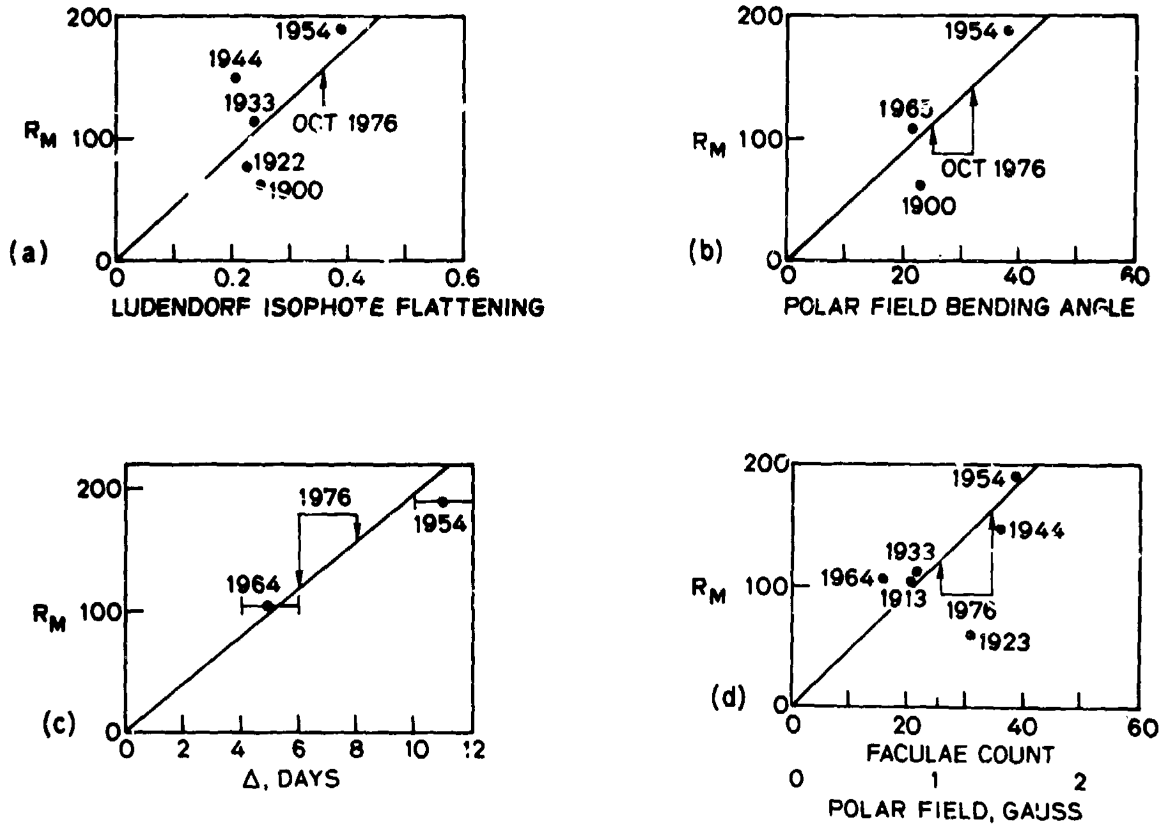

Fig. 1. (a) Sunspot number at maximum vs. the Ludendorf isophote flattening index at an eclipse near the preceding solar minimum.

(b) Sunspot number at maximum vs. Polar Field Bending Angle (P.F.B) at times of eclipse near solar minimum.

(c) Sunspot number at maximum vs. Δ, a measure of the yearly variation of the predominant polarity of the interplanetary field near earth, a measure of polar magnetic field strength.

(d) Sunspot number at maximum vs. facular count in polar regions, and related polar field strength, at the preceding solar minimum.

The arrows in these graph indicate cycle 21's indices from which the cycle's sunspot maximum has been estimated.

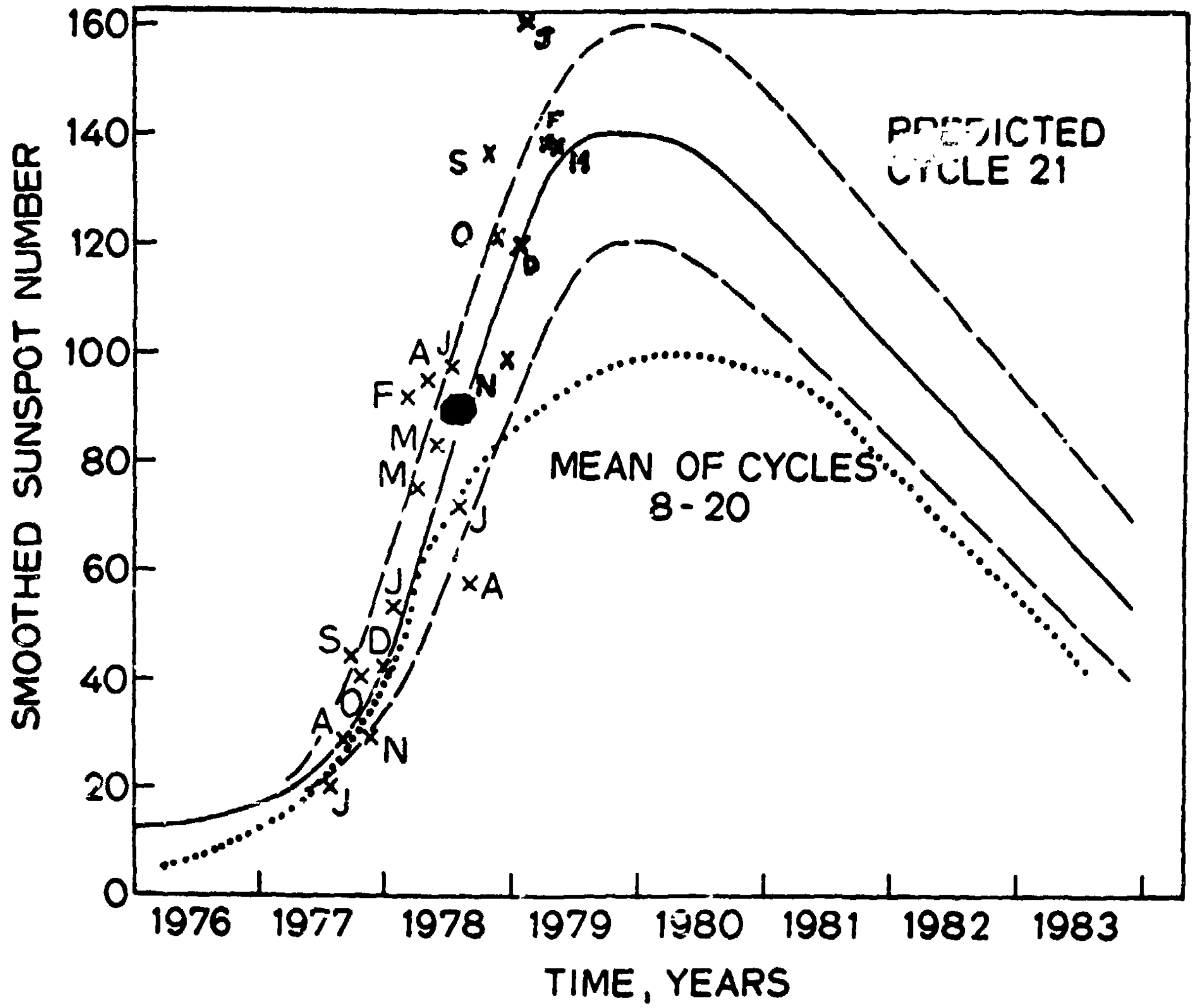

Fig. 2. Predicted smoothed sunspot number based upon dynamo theory from 1976 to 1983 (solid curve). Estimated yearly average uncertainties (dashed curves) are smaller than in many other predictions and show that a larger than average cycle (dotted curve) is definitely predicted. Crosses show individual monthly sunspot numbers, labelled with the first letter of the month. The large dot shows the yearly 1978 average agreeing remarkably well with the prediction.

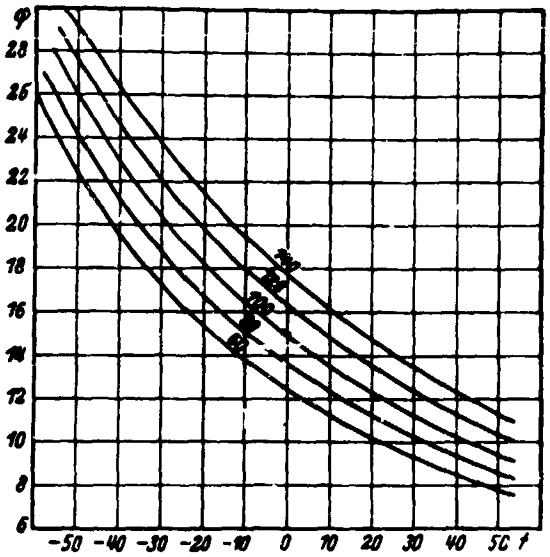

Fig. 3. Migration of spot zone for different R_m (heights of sunspot maximum). Abscissae: time measured in solar rotation from sunspot maximum; ordinates: latitude (Waldmeier, 1939).

Fig. 4. H_α photo of the sun on May 3, 1979. The text discusses the usefulness of these observations (Baumgardner, 1979).

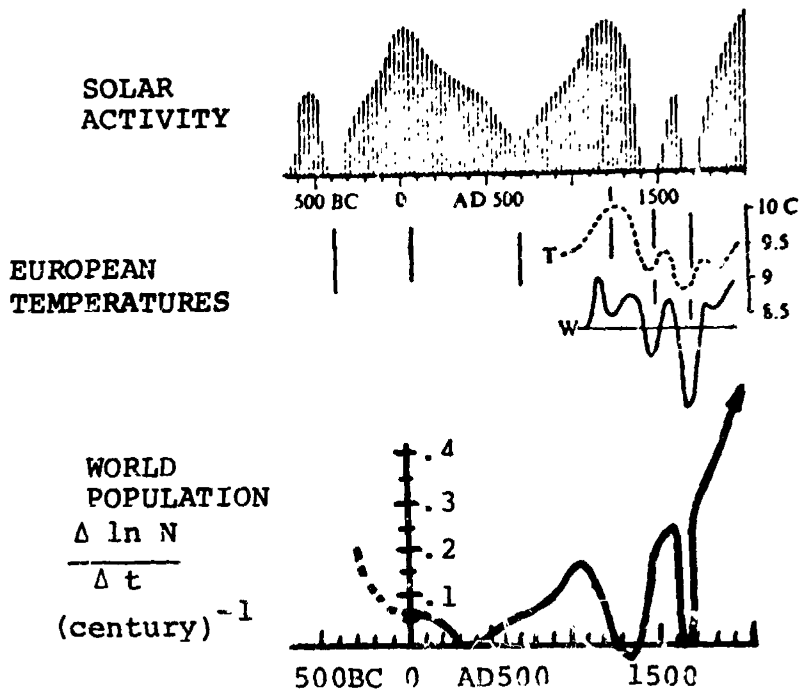

Fig. 5. Solar Activity variations (after Eddy, 1977), European temperatures, and logarithmic rate of world population growth (after McEvedy and Jones, 1978).

QUESTIONS AND COMMENTS

<u>COMMENT BY</u>: R. Noyes, Harvard-Smithsonian Center for Astrophysics

<u>DIRECTED TO</u>: K.H. Schatten

COMMENT: As you know, we have looked at the Greenwich Data of individual spots and found no evidence of a 12-day periodicity.

RESPONSE: You may not have seen the 12-day periodicity in spots due to the nature of <u>your</u> <u>analysis</u> or to the possibility (although we feel it is remote) of ours being a statistical fluke. Yours differs from ours in a number of ways:

(1) You use only the birth of spots.

(2) Rather than a correlative analysis of your data, you have used a superposed epoch technique.

(3) Your data span is more limited.

Phase drifts may exist as evidenced by the difference between our period and Dicke's. This could prevent your technique from detecting a 12-day signal. A fairly sophisticated approach is needed in the use of individual spot data and, for all we know, the effect may show up only in the <u>grouping</u> of spots (in sunspot numbers) not evidenced in individual spot locations!

<u>QUESTION BY</u>: J. E. Humble, AFGL/University of Tasmania

<u>DIRECTED TO</u>: K. H. Schatten

QUESTION: Have you subdivided your data into shorter groups to see if effects are visible in both sets?

ANSWER: Yes, we have divided in numerable ways and find the largest differences between dividing the data into odd and even cycles. This suggests to us that the relation, if real, is magnetically related.

N80-17953

THE OPPORTUNITIES OFFERED BY SCADM FOR THE STUDY OF SURFACE PHENOMENA RELATED TO INTERIOR STRUCTURE AND DYNAMICS

Timothy M. Brown
High Altitude Observatory

I. Introduction

Granting that useful scientific information about the Sun's interior may be obtained by studying the solar surface, the prospect of a SCADM mission to perform these studies immediately raises two questions: Can the observations required for these studies be obtained from a spacecraft? If so, are there compelling reasons to observe from a spacecraft rather than from the ground? Unsurprisingly, the answers to these questions vary, depending on which observational problem one is concerned with. One finds, however, that the answers are based on only a few fundamental issues, and that by understanding these issues the merits of any given experiment may be fairly quickly assesed. My aim in this discussion is to review the relevant issues, and to illustrate their application by reference to a set of potentially interesting experiments. The experiments chosen are intended to be both plausible candidates for the SCADM mission and representative of the problems one may encounter, but I emphasize that this list is by no means an exhaustive summary of reasonable interior diagnostics for SCADM. Finally, for reasons given below, I will devote little space to purely instrumental considerations. In most of the cases to be considered, it seems likely that observational limits will be set by solar processes rather than by instrumental deficiencies. If in any instance I believe that this may not be true, I will say so explicitly.

II. Potential SCADM Experiments

The list of experiments I will consider is given in the accompanying Table, along with estimates of the observational requirements for each. As indicated in the Table, the physical processes probed by these experiments may be conveniently grouped as Large-Scale Flows, Oscillations, and Chromospheric/Coronal Diagnostics. As will be seen, the fundamental concerns and observational requirements are similar within each class, even though different experiments within a class may tell us quite different things about the Sun.

The observational requirements listed in the Table are in most cases set by the amplitude, physical size, and temporal scale of the physical process being observed. A notable exception is the time resolution required for studies of long-lived flow patterns such as giant cells and solar rotation. Though these flows change on timescales of weeks or longer, it is highly desirable to monitor them often enough to resolve the five-minute oscillations, so that the oscillations do not contribute undue noise to the velocity field measurements. It is also important to note that the noise requirements given in the Table refer to appropriate averages over the area and lifetime of the feature in question (the size and lifetime of a giant cell, say, or the span of space and time over which a five-minute oscillation mode is coherent). Thus, although the allowable noise as shown in the Table may seem frighteningly small, the limits on measurement error per pixel per observation time generally come out to be quite reasonable. Of course, systematic errors such as gain changes and baseline drifts cannot be expected to average to zero, and must be kept within the stated bounds at all times.

TABLE

GROUP	EXPERIMENT	OBSERVATIONAL REQUIREMENTS	
LARGE SCALE FLOWS	Rotation, Meridional Flows, Giant Cells Intensity Fluctuations and Tracers	Spatial Resolution	15"
		Temporal Resolution	60s
		V Accuracy - Global Avg.	10 cms^{-1}
		V Stability	10 $m\ s^{-1}$
		I Accuracy	0.1 %
	Plasma - $\vec{B}$ Interactions	Spatial Resolution	4"
		$\vec{B}$ Accuracy	0.1 gauss
OSCILLATIONS	Interior Structure	Spatial Resolution	4 - 8"
		Time Resolution	60s
		ω Resolution	$(2 - 10\ day)^{-1}$
	Rotation vs. Depth	k Resolution	$(R_{\odot})^{-1}$
		V Accuracy per k-ω bin	$(1\ cm\ s^{-1}\ rms)$
	Diameter Oscillations	Diameter Accuracy per ω bin	10^{-3}"
		I Accuracy per ω bin	10^{-2}%
CHROMOSPHERIC & CORONAL TRACERS AND DIAGNOSTICS	Tracers - Coronal Holes, X-ray Bright Points	Spatial Resolution	2 - 10"
		Temporal Resolution	60 m
	EUV Luminosity	I Stability	10%
		Spatial Resolution	Whole Disk

III. Central Issues For SCADM Measurements

For the observations listed in the Table, the problem (as with most physical measurements) is to separate the solar processes of interest from a host of competing effects. This difficulty is aggravated by the long timescales of the interesting solar phenomena. Indeed, the relevant timescales are typically so long that it becomes infeasible to obtain uninterrupted observations for the required lengths of time. Thus, one must deal not only with noisy data, but also with data that are significantly incomplete. In order to determine the relative merits of ground or spaceborne observations of a given solar phenomenon, one must therefore understand both what sources of noise enter into the measurement, and how the influence of these sources is affected by the presence of large gaps in the observed timestrings.

A. Noise Sources

From the list of experiments given above, it is evident that the bulk of the required observations deal with accurate measurements of intensities or spectrum line positions. The former are necessary for measurements of diameter or intensity oscillations and for many tracer observations, while the latter are required for measurement of magnetic fields and line-of-sight velocities. The accuracy of such observations may be limited by photon noise, instrumental noise, environmental effects, or solar processes. All of these potential sources of error deserve some consideration.

Photon noise as it applies to velocity and magnetograph observations has been treated by Beckers (1968), and as it compares to other sources of error by Beckers and Brown (1979). Beckers (1968) found that for a 30 cm telescope aperture and a 1" square pixel, the time required to measure a magnetic field to an accuracy of 5 gauss (or a velocity to 20 m s^{-1}) is about

2 s. This estimate is supported by the experience of several observers (e.g. Deubner 1967). For the SCADM experiment, one might take a 10 cm aperture, 4" square pixel size, and 60 s integration time as more reasonable. For these parameters, the errors in magnetic field and velocity are reduced to 0.7 gauss and 2.8 m s^{-1}. These errors are quite trivial, provided that all pixels can be observed simultaneously, i.e., that no spatial scanning is required to build up the velocity or magnetic field image of the Sun. If scanning is required, then each pixel can be observed for only a small fraction of the possible time, and photon noise may become significant. Fortunately, the availability of 2-dimensional photoelectric detector arrays and new instrumental techniques should make such scanning unnecessary. Intensity measurements are even less sensitive to photon noise than are velocity measurements, since they do not involve differences between separate intensity samples.

Instrumental and environmental noise are often difficult to separate. I draw the distinction chiefly because there are noise sources such as amplifier noise that will be very similar for ground and spaceborne observations, but there are others such as seeing that will clearly be present in one but absent in the other. Of these problems, those common to both types of instrument are the less serious. Detector and amplifier noise can be reduced to values comparable to photon noise, at least for some available detector arrays (e.g. Aikens, et al., 1976). Similarly, noise from mechanical vibration, electrical crosstalk, and similar sources can be held to negligible levels by proper design.

Of the environmental influences felt by a groundbased instrument, seeing and scintillation are the most obtrusive. However, for the spatial and temporal resolution of interest to SCADM, even these effects are not too serious. The largest velocity error caused by seeing external to the telescope results from image motion, which causes one to sample different parts of the granular motion field at different times. Assuming the rms velocity of the granulation to be 450 m s^{-1}, the correlation length to be 0.5", and the seeing image motion to be 0.5", the instantaneous noise expected from this source for an aperture 10" square is 20 m s^{-1}. Taking the seeing itself to have a correlation time of 0.1 s and using a 60 s integration time, the resulting velocity error is 0.7 m s^{-1}. Seeing within the instrument itself, particularly spectrograph seeing, can be much more damaging. However, this can be eliminated either by evacuating the optical train, or by using instruments that are much less sensitive to seeing than are spectrographs (e.g., interferometers). For velocity measurements, diurnal and other temperature changes can cause serious problems via differential thermal expansion of parts of the instrument, subtle changes in alignment of or interference between optical elements, or alterations of the gain and zero point of electronic devices. Intensity measurements are not so sensitive to these problems, but are susceptible to changes in atmospheric transparency. Finally, and most important, clouds and the day-night cycle assure that at any given site, the Sun will be unobservable for two-thirds of the time. By observing from polar sites it is possible to get occasional long observing runs (four or five days), but there are difficulties inherent to this approach. Principally, if such runs are available only a few times per year they do not provide the near-continuous monitoring that many experiments appropriate to SCADM require. Problems that are discouraging but not critical are the large solar zenith angles encountered, the comparatively harsh environment, and a variety of logistical problems.

By observing from a satellite one avoids atmospheric noise, but encounters a number of new difficulties. Thermal cycling tends to be more severe on a satellite than on the ground, both because the temperature excursions are larger and because the timescales on which these excursions take place are shorter. Further, the effects seen can depend in a sensitive way on the Sun-orbit geometry, and thus vary with time. Similarly, it is difficult to maintain mechanical isolation between different systems on a satellite--accurate pointing, in particular, seems to be hard to achieve if any mechanical noise is present on a small satellite. White and Athay (1979) have discussed both of these problems and their effects on the OSO-8 observations. Once again, these problems should be minimized for experiments of interest to SCADM, because of the comparatively coarse spatial resolution required and the availability of measurement techniques that are insensitive to thermal and mechanical fluctuations.

The large radial velocities caused by a spacecraft's orbital motion and the rapid day-night cycle are environmental effects that cannot be eliminated by proper experiment design. The orbital motion can introduce spurious velocity signals of as much as 8 km s^{-1}, as compared with the Earth rotation signal for a groundbased instrument of about 400 m s^{-1}. However, using tracking data it should be possible to remove this orbital signal with an accuracy of better than a few m s^{-1} (SCADM Meeting Proceedings #2, p. 63). Further, the variation of this signal across the solar disk will never be more than about 80 m s^{-1}, and will be predictable with the same fractional accuracy as the orbital velocity itself. Thus, the orbital signal will only enter into measurements of the average velocity of the entire visible solar disk. Most of the error will occur at the satellite's orbital period, with harmonics introduced by deviations of the orbit from circularity and by side-lobe generation from the day-night cycle. The day-night cycle itself will tend to corrupt the data in the same way as for a groundbased instrument, but with three important differences. First, the Sun is visible from a low-inclination orbit for about two-thirds of the time, about twice as much as one can expect from even a good ground-based site. Second, the frequency of interruption in the data strings is much higher from a satellite than from the ground--once per 90 minutes or so as opposed to once per day. Last, because of the absence of clouds, the interruptions in a satellite data string will be much more regular than for groundbased strings. All of these differences have favorable implications where SCADM experiments are concerned, as will be explained below.

The last and most significant source of noise for SCADM surface observations is the Sun itself. The quantities of chief interest to SCADM are typically phenomena with small amplitudes and large spatial and temporal scales. Unfortunately, the Sun provides a host of phenomena with large amplitudes and small spatial or temporal scales. These may appear as noise in the desired measurements, and the form this noise takes is in some cases quite sensitive to the way in which the data are obtained.

For velocity measurements the most important solar sources of noise are granulation, supergranulation, and the five-minute oscillations. For the current discussion, the properties of interest concerning these phenomena are their amplitude and temporal power spectrum, as seen with an entrance aperture 5" to 10" square. Granulation has a typical rms velocity of about 0.45 km s^{-1}, with a correlation length of about 0.5" (Beckers and Parnell 1969). This implies a signal seen by a 10" square aperture of about 25 m s^{-1}. Since the lifetime of a granule is typically 8-10 minutes, most of the power in the granulation velocity field is concentrated below one cycle per 10 minutes. At much lower frequencies the velocity field is dominated by supergranulation, with amplitudes of perhaps 200 m s^{-1} (depending, of course, on whether one observes at disk center or near the limb. See Deubner, 1971), and time scales of a day or longer (Worden and Simon, 1976). Though difficult to confirm observationally, it seems likely that the temporal power spectrum of velocity is in fact a continuum in to at least the frequencies of a cycle per day or so that characterize supergranulation. If this is true, then the two points corresponding to granulation and supergranulation suggest that the observed power is roughly inversely proportional to frequency. Five-minute oscillations also contribute large amounts of power when integrated over a 10" aperture, but the oscillations are much more nearly band-limited than are other solar noise sources. Thus, although the rms velocity due to oscillations as measured with this aperture may be 100 m s^{-1} or so, the oscillatory component at periods longer than 15 minutes is negligible. By measuring the velocity field often enough to oversample the oscillations, one can either remove the five-minute oscillations or study them in detail, as desired.

The intensity measurements that one requires for monitoring the solar diameter are also subject to solar noise. Most observations of the photospheric intensity field have been explicitly concerned with granulation, so that few accurate measurements of low-wavenumber intensity fluctuations are available. However, the available observations (e.g. Deubner and Mattig 1975, Aime, et al. 1978) indicate that large amounts of power can be seen at spatial scales larger than 10". Observations by Brown (1979) near the solar limb also show this power, and indicate that most of its temporal variations are concentrated at periods longer than 10 minutes. The presence of this background noise in the same frequency and wavenumber range as the oscillations one seeks is the most serious impediment to understanding the diameter oscillations.

The chief conclusion to be drawn from this discussion of noise sources is that the largest source of uncertainty in any surface measurement of interest to SCADM will not be instrumental problems, but rather interference from other solar processes. To make successful measurements, one must be able to reject this interference.

B. The Effect of Interrupted Timestrings

As seen above, the dominant sources of noise in SCADM measurements of surface motions and intensities are likely to be solar processes. In most cases one can distinguish between the process that is of interest and the many that are not only on the basis of differences in spatial or temporal structure. Further, one's ability to define spatial structures on a global scale is often compromised by geometrical observing constraints. Measurements of vertical oscillations, for example, are hindered by forshortening and curvature effects except in the immediate vicinity of disk center. Problems of this sort make it very important to get as much information as possible from the Sun's temporal behavior, and to understand how realistic interruptions in the data stream affect one's ability to do this.

Fourier transforms provide the best formalism for addressing these questions. The notation used in the following discussion is that of Bracewell (1965), who also gives a through discussion of the points to be summarized below. A more condensed version of the basic notions may be found in Brault and White (1971). The reader who is not already comfortable with the ideas discussed here is urged to consult these sources.

In observing any solar process, one is presumably looking at events that have gone on (and will continue to go on) for an indefinite period of time. Call the measurable values associated with these events R(t). Unfortunately, one's observations do not go on indefinitely, nor even, where global solar properties are concerned, without interruption. What one actually sees is the string R(t) multiplied by a <u>window function</u> W(t), which is unity when observations are being performed, and is zero otherwise:

$$S(t) = R(t) \cdot W(t). \tag{1}$$

In most cases of current interest we wish to know the effect of this window function on the measured power spectrum of the process R. This can be found from the convolution theorem

$$\widetilde{f * g} = \tilde{f} \cdot \tilde{g}, \tag{2}$$

i.e., the Fourier transform of the convolution of two functions is the product of their Fourier transforms. Inverse transforming both sides and redefining domains gives a form that is more useful for the current purposes:

$$\widetilde{f \cdot g} = \tilde{f} * \tilde{g}. \tag{3}$$

Or, in words, the transform of a product of two functions is the convolution of the individual transforms. Thus, by a trivial substitution,

$$\tilde{S} = \tilde{R} * \tilde{W}. \tag{4}$$

The desired transform $\tilde{R}$ is thus smeared out by the transform of the window function W. A particularly unpleasant feature of this smearing is that it occurs in the transform, whereas one's observational concern is generally with the power spectrum. This means that the power one measures at a given frequency depends not only on the power at other frequency points, but on the p at those points as well. Noise from this source can therefore be quite significant, even when the sidelobes of the window function transform appear to be small.

Since the transform of the window function is so important, it is useful to have a way to estimate what the transform looks like. For the type of window function that will be most commonly encountered in observations of global solar properties, this is easily done. Such a window function, shown in Figure 1, consists of a series of equally-spaced observation periods separated by uniform gaps during which no observations occur. The separation between observing periods, d, is one day for a groundbased instrument, or one orbital period for a spaceborne one. The observing period, f, is determined by the fraction of the time the Sun is visible each day (orbit) from the given observing station. The total lenth of the observing run, T, is determined by weather, instrument failure, solar rotation, or any other factor affecting the visibility of the solar process in question. Since the origin for measuring time in these circumstances is essentially arbitrary, it is always possible to position this window function so that it is symmetric about $t = 0$, and only the real (cosine) part of the transform survives.

The window function itself is most easily described in terms of a combination of two simpler functions described by Bracewell (1965), the rectangle function of unit height and base $\Pi(t)$, and the sampling function of unit spacing $Ш(t)$. $\Pi(t)$ is simply a boxcar of unit height and length, centered on the origin, while $Ш(t)$ is an infinite sequence of delta functions with unit separation. If T were infinite, the window function in Figure 1 could be formed by an appropriately scaled convolution of II and III:

$$W_\infty(t) = \mathrm{II}(t/f) * \mathrm{III}(t/d). \tag{5}$$

The transform of this window function would then be given by the product of the individual transforms (by Equation (2)). These are (Bracewell, 1965, pp 359, 360)

$$\mathrm{II}(t/f) = \frac{\sin(\pi\omega f)}{\pi\omega f} \equiv \mathrm{sinc}(\omega f), \tag{6}$$

$$\mathrm{III}(t/d) = \mathrm{III}(\omega d), \tag{7}$$

where ω is the variable denoting temporal frequency. The transform of this infinite window function is thus a sequence of delta functions with spacing inversely proportional to d, multiplied by an envelope consisting of a sinc function with width inversely proportional to f. To obtain the finite-length widow function of interest, W_∞ must be multiplied by another rectangle function, this time of length T:

$$W(t) = W_\infty(t) \cdot \mathrm{II}(t/T) \tag{8}$$

By equation (3), the transform of this window function is

$$W(t) = [\mathrm{III}(\omega d) \cdot \mathrm{sinc}(\omega f)] * \mathrm{sinc}(\omega T). \tag{9}$$

This transform is shown at the bottom of Figure 1. It consists of a series of sinc functions of width T^{-1}, separated in frequency by d^{-1}, and contained within an envelope of width f^{-1}. The most useful part of the analysis leading to this function is that it allows one to see clearly the relationship between the window function transform and the length, separation, and total duration of the observing periods comprising the window function itself.

Having arrived at the desired window function transform, one might ask how this transform can be modified by different analysis techniques. It is easy to show that if attention is restricted to methods that are linear, then any such method is equivalent to multiplying the available data points by a set of weights. This process is often termed belling the data, or apodizing the window function. From the foregoing discussion it is clear that the effect of such belling will vary, depending on whether the bell is applied to the individual data strings of length f, to the entire composite string, or to both.

Applying the same bell function to each of the individual timestrings in a long data set has the effect of altering the envelope of the narrow sinc functions (henceforth termed <u>sidelobes</u>) shown in Figure 1. It is usually advantageous to do this, since any smoothing of the window function generally results in suppression of the distant sidelobes, and these are often the most troublesome. This process usually causes some enhancement of the first sidelobe relative to the central lobe, however. Working to somewhat different ends, by allowing belling functions that are sometimes negative, it is possible to eliminate any given sidelobe (even the first). This can be useful if contamination from that one sidelobe is a particular problem. This technique must be used judiciously, however, since it always raises the other sidelobes and significantly reduces the magnitude of the central lobe.

Applying a smooth bell function to the entire sequence of observing periods changes the shape of the individual sidelobes. One usually wishes to do this, since otherwise there can be a significant contribution to the measured signal from the regions between the nominal sidelobe postions.

Finally, there are a variety of nonlinear analysis methods which under some circumstances may be useful for spectrum analvsis. The maximum entropy technique (see Ulrych and Bishop, 1975, for a review) is perhaps the most notorious of these. These methods as a class seem to give untrustworthy results if the spectrum under consideration is very complicated, or is unduly contaminated with noise. However, there may be some cases of interest, notably the mode structure of the five-minute oscillations, in which the true spectrum is sufficiently noise-free and clearly defined for these techniques to be effective.

IV. Applications to Experiments

It now remains to see what effect the issues of noise and timestring character may have on the experiments of interest. This is best done by examining the experiments individually, but it will become clear in the course of this examination that most of the experiments have features in common. In particular, most of those experiments requiring only visible-light observations can be done, in some fashion or other, either from space or from the ground. This is a natural consequence of the dominance of solar noise sources; such noise cannot be avoided simply by relocating the instrument. The sensitivity to solar noise sources may, however, depend on the instrument's location. Let the reader be warned, therefore, that the relevant question will often be how well an experiment can be done from space or the ground, rather than whether it can be done at all.

A. Rotation, Meridional Flows, Giant Cells

To learn about meridional flows, giant cells, and spatial or temporal variations in the solar rotation, one must measure the solar velocity field with comparatively coarse spatial resolution. These measurements must be averaged over a long enough time to reduce the noise from other solar motions to acceptable levels, but must be completed quickly enough that the flows do not change much during the observing period. One is therefore interested in motions of approximately zero frequency, shown at the origin in Figure 2.

Figure 2 also shows in schematic fashion the solar background noise for velocity measurements. Because of the window function considerations given above, the signal measured will be contaminated by this background in at least two ways. First, because of the finite total observing time T, a small range of frequencies near $\omega = 0$ will be included in the measurement. Second, and probably more serious, sidelobes generated by the day-night cycle will contribute noise from frequencies that are considerably removed from $\omega = U$. The largest contributor to this kind of noise will be the first sidelobe, located at about 7×10^{-5} s^{-1} for a groundbased instrument, or about 1.1×10^{-3} s^{-1} for a satellite. Since the noise contribution is proportional to the amplitude of the solar signal at the position of the sidelobe, it is evident that a satellite measurement would be less noisy than a groundbased one by a factor of about four. Restated, for these measurements it would take at least sixteen times as long to attain the same noise level from the ground as from a satellite. This conclusion is strengthened by the influence of the comparatively small duty fraction available from the ground, which causes more sidelobes to become important. Further, it is difficult to obtain extremely long data sets from the ground, so that for groundbased measurements the individual sidelobes will tend to be wider.

All of these considerations suggest that groundbased measurements of large steady flows will be noisier than their spaceborne counterparts by a factor of between 5 and 10 for the same length of observation, or that groundbased measurements will require 30 to 100 times more observing time for the same noise level. The interpretation of these numbers is a bit difficult, since most of the flows of interest have not yet been seen. The noise level ultimately required to allow a clear definition of the flows is therefore a matter of conjecture. It is clear, however, that total observing times of more than a month or so cannot be tolerated, since many of the interesting phenomena probably change on timescales that are shorter than this. Such long observing times are likely to be necessary from the ground if the flow velocities in question are less than 2 or 3 m s^{-1}. In short, large-scale flow measurements obtained from orbit can be much better than those obtained from the ground, and for some kinds of flow this difference may be crucial to understanding the physics involved.

B. Intensity Fluctuations and Tracers

For the purpose of SCADM (and as distinct from intensity oscillations, which will be discussed later), intensity fluctuations are useful chiefly as tracers of the gas flow on the Sun. In this context they provide some measure of the flow in the two directions perpendicular to the line of sight. Such measurements are affected to some degree by the continuum fluctuations of the quiet Sun, and are thus subject to some of the same considerations outlined in the previous section. The effects are much less important for tracers than for velocity measurements, however. This is true in part because the features used as tracers are usually obvious, contrasty features like sunspots, and in part because small features tend to make the most accurate tracers, and the lifetime of such features is typically short. The maximum possible length of observing run in such cases is thus set by the feature lifetime rather than by local observing constraints. Notable exceptions to the small-feature rule are large, stable sunspots, which have been used as rotation tracers by several investigators (e.g. Newton and Nunn, 1951). Unfortunately, the motion of sunspots and other tracers is usually accompanied by shape changes that can be monitored only with high-resolution imagery. The resolution required is perhaps 2" or less, which is almost certainly impractical for SCADM. There may be some advantage to satellite observations because tracers may easily disappear or become distorted beyond recognition during the time the Sun is invisible from a groundbased instrument; this is less likely to happen from a satellite because the data gaps are much shorter. This argument, too, is unconvincing, largely because of the many widely scattered observing stations already in operation that can provide the required data. For tracer measurements, one probably benefits more from cooperation between groundbased observers than from flying a satellite.

C. Plasma-Magnetic Field Interactions

Any complete model of the solar dynamo must describe the interaction between the solar magnetic fields and the fluid flow in the photosphere and underlying convection zone. One of the few observational tests of such a description is to monitor the magnetic field distribution and the photospheric velocity field, and see if the evolution of one can be predicted from the behavior of the other. Since this experiment requires one to make accurate mean velocity determinations with moderate resolution in short periods of time, the arguments in section A above indicate that these measurements, at least, may be best done from a spacecraft. A further argument to the same effect is that without essentially continuous observations of the photospheric velocity fields, it will probably be impossible to deduce the subsurface velocities with the required accuracy.

The case for measuring the magnetic fields from space is not so clear, at least as regards their use as comparative tracers. The reasons for this are the same as for intensity tracers: large, slowly changing features can be measured almost as well from the ground, while small, rapidly changing ones could probably be done significantly better from orbit, but require excessive spatial resolution. An exception to this last point may occur if it is sufficient to observe the fields over only a limited portion of the Sun rather than the whole solar disk. In this case the number of pixels required may not be unreasonable, even for an essentially synoptic mission like SCADM.

D. Interior Structure via Oscillations

The possible use of five-minute or longer period oscillations as diagnostics for the Sun's internal structure has been discussed by several authors (e.g. Rhodes, et al. 1977, Christensen-Dalsgaard and Gough 1976). For both kinds of oscillation, the observational aim is to determine the frequency of each oscillation mode as precisely as possible. The frequency resolution required to separate one mode from another generally corresponds to observing runs with lengths of several days. Interrupted data strings are therefore unavoidable, and the influence of the data window function is of utmost importance.

The kind of information about the mode structure that one requires is shown in Figure 3, which is taken (with additions) from Deubner, Ulrich and Rhodes (1979). The plot shows observed power in solar velocity oscillations as a function of horizontal wavenumber (the horizontal axis) and temporal frequency (the vertical axis). The dominant feature of this plot is the fan-shaped pattern of ridges near $\omega = 0.02\ s^{-1}$, with each ridge corresponding to an unresolved multitude of oscillation modes. All of the modes in a given ridge have wavefunctions with an equal number of nodes as a function of depth in the Sun. A quantum mechanical analog is that the modes in a given ridge all have the same radial quantum number, but different angular numbers. Having described the ridges as made up of many distinct modes, I must quickly add that this may not be strictly true. No observations to date have adequate frequency or wavenumber resolution to split this mode structure, and thus verify that the modes are not smeared into one another by damping effects. It seems likely that the modes are in fact distinct, however.

The observational problem, then, is to obtain adequate resolution in frequency and wavenumber to separate individual modes, if such there be. The wavenumber resolution one can obtain is limited, however, because at a given time only a small portion of the Sun's surface is close enough to disk center for accurate observations to be made. The size of this portion is such that typically five or six distinct modes on each ridge lie within a wavenumber resolution element. This situation is shown schematically in Figure 4. It is clear that if the modes are to be resolved at all, this must be done on the basis of their frequencies rather than their wavenumbers. Groundbased observations are at a great disadvantage in attaining this frequency resolution because the sidelobe spacing for such observations is very similar to the solar mode spacing. The sidelobes from different modes within one wavenumber bin will therefore overlap, making interpretation of the spectrum difficult or impossible. For observations taken from orbit, on the other hand, the sidelobes fall far outside the bounds of any one ridge, and crosstalk between the different modes in a ridge should be negligible. The only case in which serious crosstalk can develop is if the sidelobe spacing is the same as the spacing between ridges. Inspection of Figure 3 shows that for most of the area of the k-ω diagram this is not a problem. These same arguments apply if the modes are not distinct, since in this event the intrinsic ridge width due to damping must be at least as large as the width due to unresolved modes.

In summary, observations of five-minute oscillations that are adequate for detailed studies of the Sun's interior structure can probably be obtained only from a spacecraft. The form of the sidelobe structure inherent in groundbased observations would make the interpretation of such data prohibitively difficult and ambiguous.

E. The Depth Dependence of Rotation

As described by Deubner, Ulrich, and Rhodes (1979) and by Gough (1978), k-ω diagrams similar to that in Figure 3 may be used to gain information on the depth profile of solar rotation. In simplest terms, this is done by comparing the frequencies of wavetrains running to the east with those running to the west, and noting that if the waves exist in a moving fluid, the two frequencies will be different. One gets depth information because different oscillation modes are sensitive to the fluid motion at different depths. The observations required to perform this analysis are high resolution and low noise measurements of the power distribution in the k-ω plane. These are virtually the same measurements needed for the mode identification experiments described in the last section, and for the most part the same conclusions apply. The only differences arise because rotation measurements do not require accurate frequencies and wavenumbers for each individual mode; an average over many appropriately chosen modes is sufficient. This suggests that accuracy suitable for some purposes may be obtained from the ground. However, the effects being sought are extremely small, and for rotation determinations of the highest possible accuracy, the low noise observations that are best obtained from orbit will probably be essential.

F. Diameter Oscillations

Oscillations in the apparent diameter of the Sun have been reported for several years (e.g. Brown, et al., 1978, Hill and Caudell, 1979). These observations are the center of a controversy, since other authors (e.g., Fossat, et al., 1977) maintain that the entire fluctuating diameter signal can be explained as an effect of the Earth's atmosphere. Although strong arguments have been advanced for the solar origin of the oscillations (Brown, 1979; Caudell, 1979), the controversy persists, and will probably continue to do so until more convincing proof can be offered one way or the other.

Assuming the origin of the oscillations to be solar, they must arise in brightness fluctuations that alter the detailed shape of the limb darkening fucntion. They may be observed using the very sensitive FFTD edge definition technique (Hill et al. 1975), by monitoring the shape of the limb darkening function directly, or, apparently, by direct observation of brightness variations at disk center (Brown 1979). In any case, the signal seems to consist of a number of narrow-band oscillations superposed on a broad and essentially random background. The signal amplitudes seen are a few times 10^{-3} arcseconds for typical peaks in the diameter power spectrum, or a few times 10^{-4} in the relative intensity, and the background noise is of similar magnitude.

All of the above considerations bear on the suitability of this experiment for SCADM. It is clear that observations from a satellite would settle the issue of whether the oscillations originate in the Earth's atmosphere. This is not a compelling reason to do the observations from orbit, however, since one can imagine groundbased observations that would answer this question equally well (simultaneous observations at widely separated sites, for example). Direct measurement of the diameter may be difficult from a satellite, in view of the large thermal cycles anticipated and the small relative diameter signal observed. This problem is aggravated by the similarity between the satellite orbital period and the periods of some of the interesting oscillations. On the other hand, these problems can probably be avoided by measuring fluctuations in intensity rather than diameter. Finally, and most important, the dominant noise source for these observations will certainly be the solar background mentioned above. Since this background appears at the same spatial and temporal frequencies as the oscillations, the sidelobe structure of the window function used is of only secondary importance in determining one's sensitivity to this noise. The important parameter in this case is simply the total length of observing time, since this determines the amount of noise that is mixed with the narrow-band signal of interest. From this point of view, observations from orbit would be superior to ground-based ones by a factor of about 2. The conclusion is that there is no very significant reason to measure diameter oscillations from orbit, but that if other instruments that measure the solar intensity field are included on a satellite (e.g. doppler instruments), then the associated brightness measurements could be had at no additional cost.

G. Chromospheric and Coronal Tracers

Coronal holes and X-ray bright points can be used as tracers of the solar rotation (see Howard, 1978, for a review). Such measurements are interesting because these features are associated with the solar magnetic fields, and apparently contain information about motion of the solar plasma at subphotospheric levels where the fields and plasma are closely coupled. There is little to be said concerning the relative usefulness of groundbased and orbital observations in this case, since the wavelengths of most interest are not visible from the ground. If such observations are to be obtained at all, they must be done from space. Further, space-proven hardware to do the required observations already exists.

H. EUV Luminosity

Measurement of the total solar luminosity in a few selected EUV lines may tell us much about how the energy balance in the chromosphere and corona changes during the solar cycle. Arguing by analogy from Lyman alpha, the changes to be expected are on the order of a factor of 2.

The instrumental stability for absolute photometry must therefore be perhaps 10 percent, which may pose some instrumental difficulties. The temporal and spatial resolution required are minimal, however. As with the previous experiment, the wavelengths in question require that this experiment be done from above the Earth's atmosphere.

V. Summary and Conclusions

The results of the foregoing discussion may be summarized by grouping the experiments listed in the Table into three categories, as follows:

Category I: Experiments that positively must be performed from orbit if the desired solar information is to be obtained, and for which the scientific justification is clear.

Category II: Experiments that are marginally less suited for operation from orbit, either because the required observations might in principle be obtained from the ground, or because it is not completely clear that high quality spacecraft data are needed to meet the scientific goals. The reader should note that I have applied these criteria more broadly than others might do. For example, experiments requiring full time use of a major groundbased facility for a period of years are here considered possible.

Category III: Experiments for which there is no compelling reason to observe from space.

With these categories, I group the various experiments like this:

Category I

Plasma-Magnetic Field Interactions

Interior Structure via Oscillations

Chromospheric and Coronal Tracers

Category II

Rotation, Meridional Flows, Giant Cells

The Depth Dependence of Rotation

EUV Luminosity

Category III

Intensity Fluctuations and Tracers

Diameter Oscillations

Several points about this grouping deserve comment. First, at least one experiment in each of the major groups can be rated Category I. This simply indicates that there is important solar physics in each of these groups that can be done effectively only from a satellite such as SCADM. Second, all of the experiments listed in Category II can arguably be placed in Category I. The distinctions I have drawn here are delicate ones, and other workers may well disagree with the results. Further, I should reiterate that not all interesting SCADM experiments appear on the current list. Finally, and perhaps most important, it should be noted that the instrumental and data-taking requirements for most of these experiments are virtually identical. Thus, if one does any of the velocity measurement experiments listed under Large Scale Flows or Oscillations, the others may be done with no more effort than is required to reanalyze the data. In short, a very few properly chosen satellite instruments could provide data of superior quality on a wide variety of solar processes.

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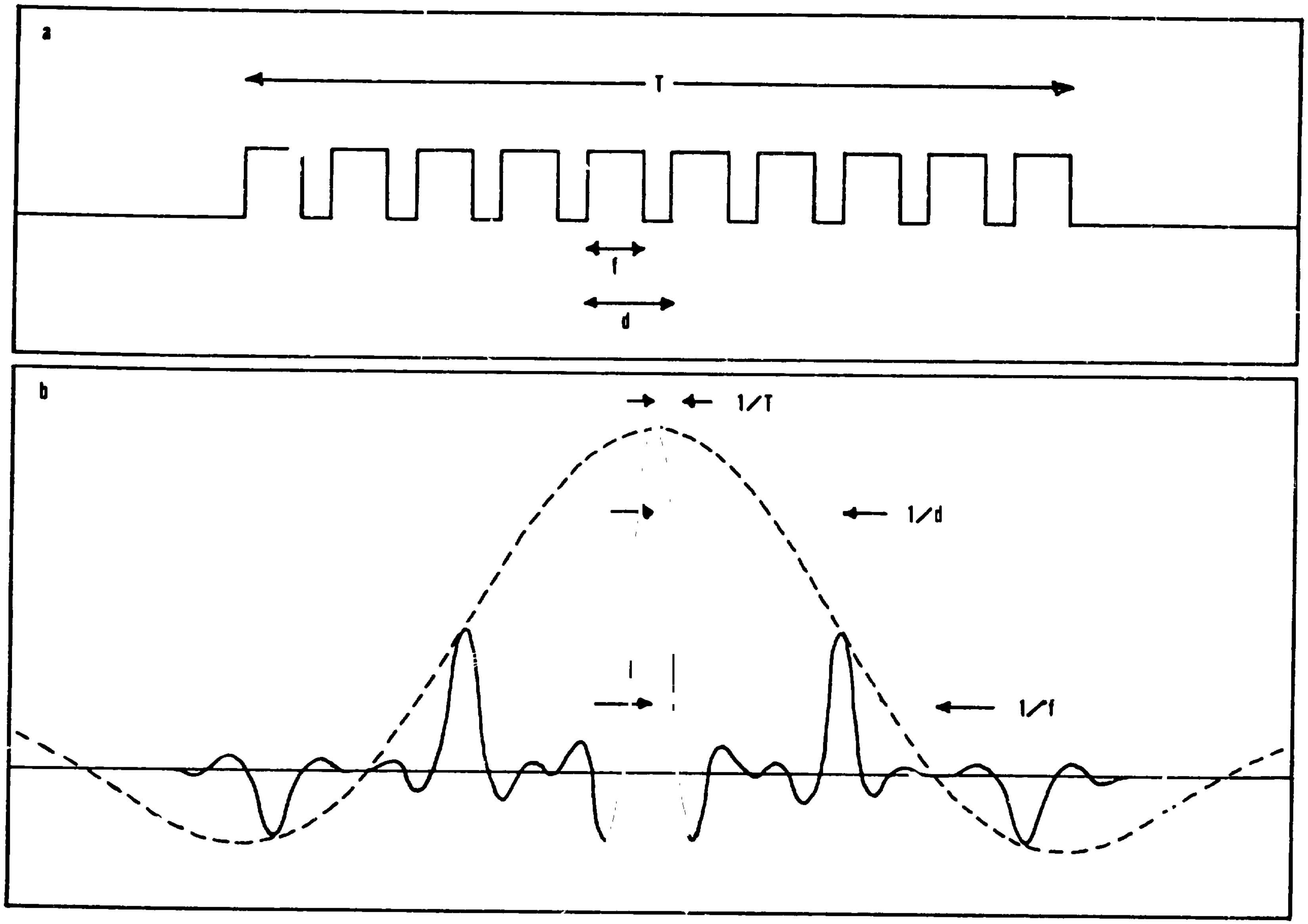

Figure 1. Example of window function and window function transform. (a) Shows typical window function. (b) Shows the transform of this window function. The dashed line shows the envelope of the transform, which has a characteristic width in frequency proportional to 1/f. The solid line shows the transform itself, which consists of spikes of width 1/T separated by frequency intervals of 1/d.

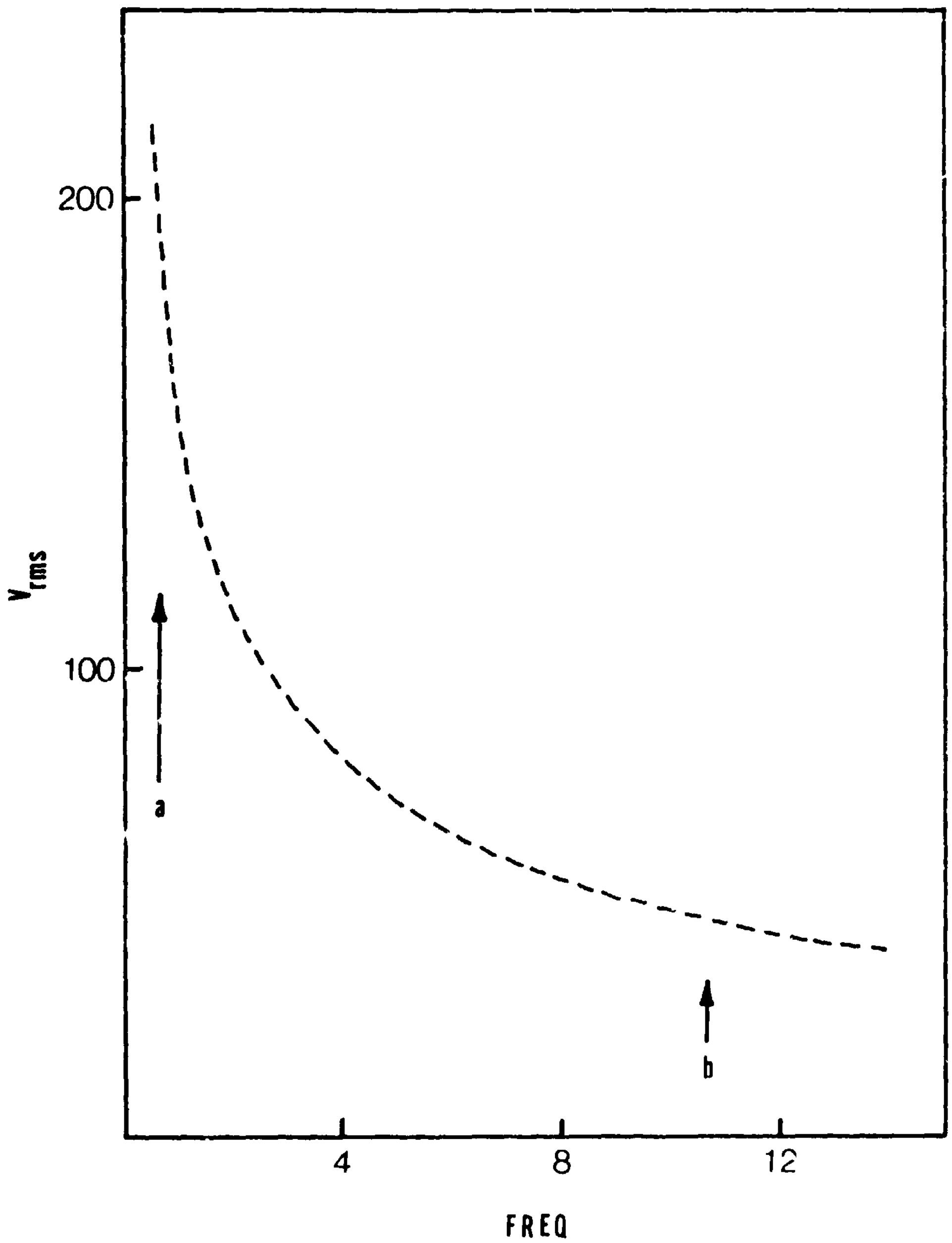

Figure 2. Solar velocity noise measured by a 10" square aperture shown as a function of frequency. Velocity is in m s^{-1}, frequency in units of 10^{-4} s^{-1}. The dashed line is a smooth interpolation between velocities and timescales appropriate to granulation and supergranulation, as explained in the text. (a) Shows the position of the first sidelobe of the window function transform for ground-based observations. (b) Shows the first sidelobe for satellite observations.

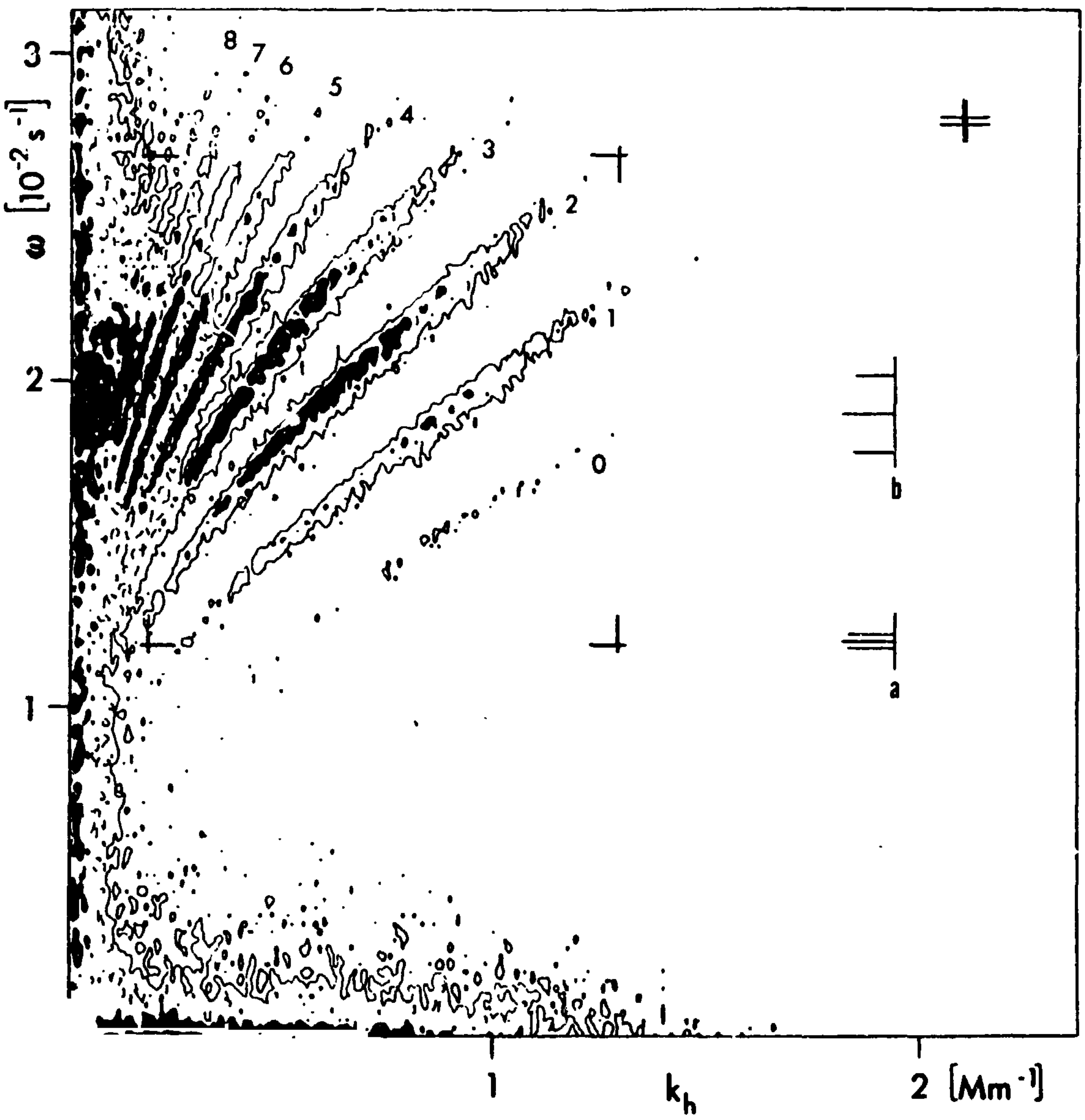

Figure 3. Power in the solar velocity field as a function of horizontal wavenumber k_h and temporal frequency ω. This figure is taken, with minor additions, from Deubner, et al. (1979). Inse~ts (a) and (b) indicate the sidelobe structure expected from ground-based and satellite observations, respectively. Because of the close spacing of sidelobes from ground-based data, (a) Shows the window function transform central lobe and third sidelobes, while (b) Shows t.. ~entral lobe and first sidelobes. Sidelobe amplitudes are not drawn to scale.

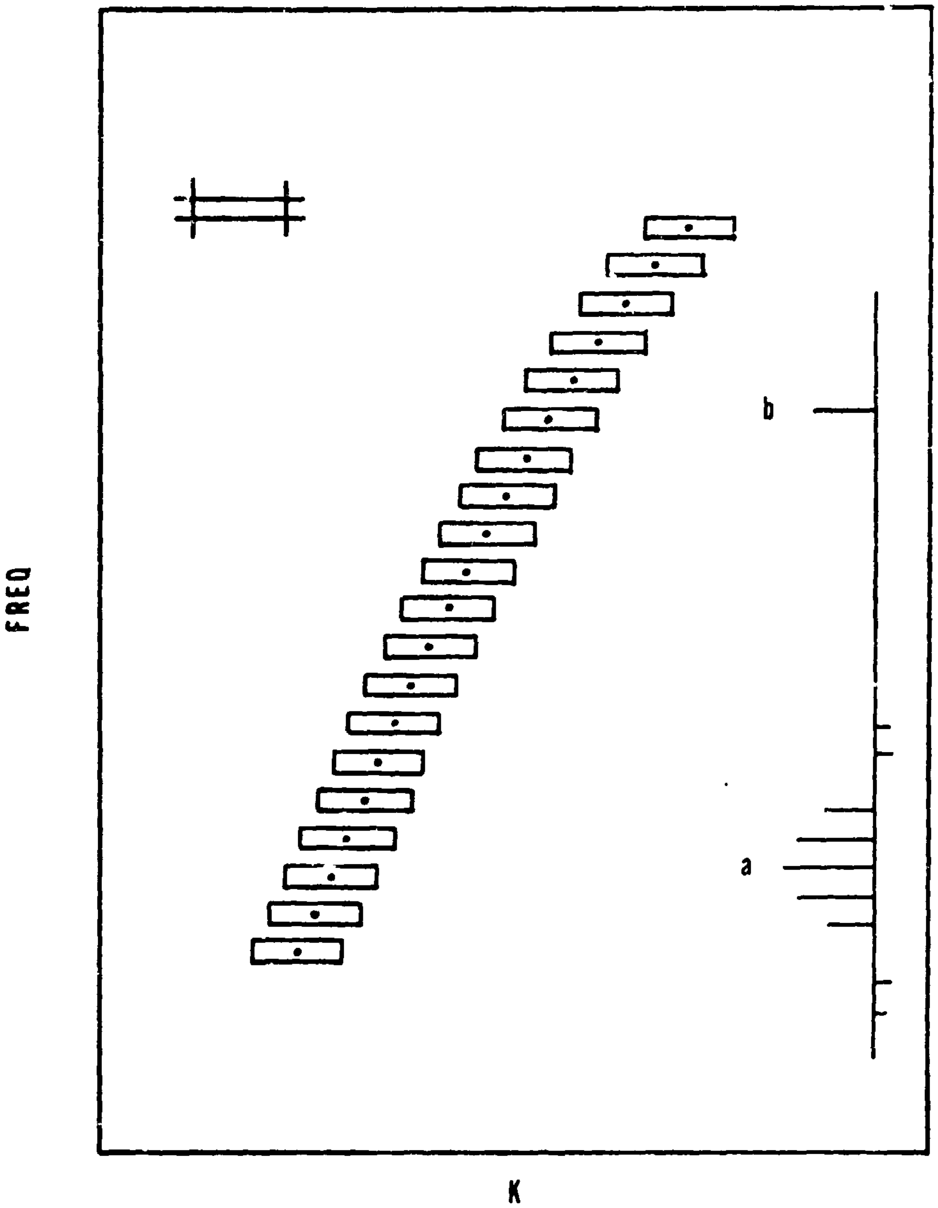

Figure 4. A greatly expanded view of one of the ridges in Figure 3, shown in very schematic fashion. This figure assumes that the ridges in fact consist of many discrete oscillation modes. The actual mode positions are indicated by the small dots; the rectangles show contours of constant observed power, assuming the resolution element in k and ω is as shown in the upper left corner. This corresponds to an uninterrupted run length of about 2 days and an observed area on the Sun of about 1000" square.
(a) Shows the sidelobe positions in ω for ground-based data. With the same central lobe position, the first sidelobe for satellite observations would appear at (b).

QUESTIONS AND COMMENTS

COMMENT BY: E. Rhodes, UCLA

DIRECTED TO: T. Brown

I wish to disagree with the placement of the determination of the depth dependence of solar rotation in Category II. Specifically, as I will point out later in this Symposium, the measurement of solar rotation below the bottom of the super-granulation layer (i.e. at depths greater than $0.03R_o$) can only be accomplished with nearly uninterrupted observing runs of 2 or more days in duration. The reasons for this are threefold: 1) the frequency splitting induced in the p-mode oscillations by rotation is proportional to the horizontal wavenumber, which means that for the deepest modes (which happen to be those with the smallest values of k_h) the frequency splitting will be much smaller and harder to measure than it is for the photospheric layers; 2) the p-modes themselves are more closely-spaced for these deeper layers; and 3) there are many fewer p-modes available for averaging the frequency splitting at large depths than there are at the photospheric depths. Thus, while some rotation measurements can indeed be made from the ground, a thorough study of those waves which penetrate the furthest into the sun will require space-borne instrumentation.

COMMENT BY: E. Reeves, HAO

DIRECTED TO: T. Brown

A magnetograph at some reasonable sampling time but very high resolution (about 1 arcsec) needs to be among the prime experiments on SCADM. The discussion of magnetic fields carried to the solar surface by X-ray or XUV bright points was not related to the array of magnetic dipoles observed. Both active regions and bright points are areas of high magnetic fields; EUV emission is known to be highly correlated with magnetic fields, and yet the AR + BP appear to be out of phase in the cycle. Also, coronal holes appear in only some open magnetic field regions. Until these obvious discrepancies are laid to rest, the magnetic field should not be inferred only from these far ultraviolet tracers.

POSTSCRIPT by Timothy M. Brown:

During the discussion period following the oral presentation of this paper, a number of points were raised that tend to change some of the conclusions I reached. As suggested in the last section, most of these tend to make certain experiments seem more attractive for a mission such as SCADM. However, since some of the points indicate significant oversights or misconceptions in the analysis of some experiments, it seems appropriate for me to summarize here the most important of these issues.

First, as noted by Dr. E. J. Rhodes, the conclusions concerning the measurement of solar rotation as a function of depth are valid only for measurements that are concerned with the outer few percent of the solar convection zone. If one wishes to measure rotation to a depth of 0.3 $R_\odot$ or so, corresponding to the bottom of the convection zone, then the required observations probably cannot be obtained from the ground at all. This is true because these depths can be probed only by examining oscillation modes with very low wavenumbers (on the extreme left-hand edge of Figure 3). In this region of the k-ω diagram the modes are so closely spaced in frequency that, for a reasonable k resolution, the individual ridges overlap. In this case any sidelobes at all are highly objectionable, and the multiplicity of closely spaced sidelobes encountered with groundbased data would surely prove fatal. In addition, the rotation accuracy obtainable with a given signal-to-noise ratio is proportional to k. Thus, higher precision measurements are required if rotation is to be measured at large depths, a situation that is aggravated by the comparatively small number of modes with small wavenumbers. In short, the depth range that is of greatest interest for theories of the solar dynamo is almost certainly inaccessable for groundbased measurements, but could be studied from space, particularly from a high inclination orbit. On this basis, the study of solar rotation via oscillations must be rated as a Category I item in the listing given above.

Second, Dr. H. Hinteregger argued persuasively that, while we may not be able to interpret the variation in EUV fluxes in terms of solar internal structure, these same fluxes are of crucial importance in understanding the Earth's response to the solar cycle. Thus, the restricted area of interest addressed in my analysis can lead to a low estimate of the usefulness of experiments that are fully justifiable on other grounds.

Finally, Dr. T. P. Caudell pointed out that if each of the peaks in the spectrum of diameter oscillations consists of the sum of many closely spaced modes, then these modes probably cannot be resolved from the ground. The argument in this case is identical to that used to determine whether individual modes in the five minute oscillations can be resolved with groundbased observations. The problem of background noise remains, however, and will still set the limit to obtainable precision in measurements of the diameter oscillation spectrum.

Second Generation Detector for Low Order Global Solar Oscillations*

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Abstract

The first observations of long period low order global solar oscillations grew out of diameter measurements made at SCLERA** over an extended period of time. As a result of these investigations, a detailed understanding of the surface properties of the oscillations has evolved, allowing development of a second generation detector. This new detector, currently under development at SCLERA, directly utilizes various surface properties of the oscillations and does not, therefore, directly involve diameter measurements. The specifications of the detector, its supporting telescope and the observing program are reviewed.

1. Introduction

The value of detecting and being able to study the low order global oscillations of the sun for the evaluation of the internal solar structure is widely appreciated. The periods of the low order oscillations that are of particular interest are between five minutes and several hours. This area of research has received much attention in the latter part of the seventies and although the subject remains somewhat controversial, the observational evidence supporting the detecton of these oscillations has become fairly substantial.

It may be argued by some that the potential for a better understanding of the solar interior and hence stellar structure in general is so great that this is of itself sufficient reason for mounting a space program to study low order solar oscillations, independent of whether or not they have been observed with ground based telescopes. It may also be felt in some quarters that the theory of stellar oscillations is sufficiently well understood that the design of a good space program can proceed relying upon pulsation theory alone. Unfortunately, this approach is not without its critics primarily because of a lack of theoretical understanding of the observed properties of oscillations. Consider, for example, the well established five minute mode where it has not been theoretically possible to estimate, to an order of magnitude, the observed amplitude of these oscillations (Goldreich and Keeley 1977).

Thus, there are clearly two possible approaches to the design of a space program for the study of solar oscillations: one is to utilize stellar oscillation theory in a domain where it is clearly inadequate; the other is to rely upon previously observed properties of solar oscillations even though some of these properties are not understood theoretically. We have elected to use the latter of these two approaches as we believe it to be the one most likely to lead to a successful space program.

Observational evidence of potential value to the design and justification of a space program for the study of solar oscillations exists in the form of: (1) temporal properties which can be used to identify global oscillations and which have been used in ground based observations to point to the existence of such oscillations; (2) the separation in frequency space of the oscillations; and (3) the amplitudes and spatial properties of the radiation intensity associated with the global oscillations. The following sections discuss the advantages that a space program can offer and the type of detector that, in such a program, could best utilize the observed properties of the oscillations

2. Temporal Properties

The major advantage of a space program for the study of solar oscillations is found in the opportunity to (1) take data for periods that are larger than approximately eight hours, (2) take data sets that are not separated in time by multiples of 24 hours, (3) have an observing period that is not controlled by the weather, and (4) have removed the seeing and differential refraction effects arising in the earth's atmosphere. It is true that the negative aspects of the first three problems listed can be ameliorated somewhat by establishing several ground based observatories and it, in fact, may be necessary to resort to such an option if an appropriate space program is not implemented.

2a. Evidence for the Design Options of Extended Data Sets

The frequency resolution in an eight hour length of data is not adequate to resolve the reported low order modes of oscillations as discussed below in section 2b. In order to extend the observing period beyond eight hours, the relevant question is, how long do these oscillations remain phase coherent. Another way of stating the question is what is the natural width in frequency of these oscillations.

There have been three observational studies on this question regarding oscillations with periods <= 1 hour (Brown, Stebbins and Hill, 1978; Hill and Caudell, 1979; and Caudell et al., 1979). Although the work of Brown, Stebbins and Hill (1978) gave results that were consistent with a phase coherence of days, the statistical significance of the results was not very strong. With the work that followed, significant phase coherence was observed for 6 oscillations during a 13 day period in the 1973 observations (Hill and Caudell 1979) and for 12 oscillations during a 23 day period in the 1978 observations (Caudell et al., 1979). The statistical significance reported for these two results received considerable attention at the 1979 workshop on nonradial and nonlinear stellar pulsations (Hill and Dziembowski 1979).

This degree of phase coherence is consistent with that expected theoretically for low order global oscillations (cf. Wolff, 1972) and it is this characteristic that most strongly supports the global mode classification of the reported oscillations. In any case, the observational evidence does give considerable support to the justification of a space observing program covering two to four weeks.

2b. Length of Extended Data Set

There are two time scales dictated by the properties of the oscillations that are relevant to the design of an observing program. The first is given by the frequency spacing of the modes without rotational splitting and the second is given by the rotational splitting of the modes of oscillation. For frequencies near 0.5 mHz, the mean frequency spacing without rotational splitting is approximately 12 μHz (cf. 2.2.3 in Hill 1978). As one moves to frequencies either higher or lower than 0.5 mHz, this mean frequency spacing decreases rapidly. Using the surface rotation rate of the Sun as an estimate of the internal rotation rate, the rotational splitting of the oscillations is expected to be approximately 0.4 μHz. The length of data sets required to resolve these structures are one day and longer for the first and 27 days for the latter.

3. Detector Design, Second Generation

The detection of the low order global oscillations has been reported in a solar diameter measurement program (Hill and Stebbins 1975, Brown, Stebbins and Hill 1978, Caudell et al., 1979). However, the complexity of solar diameter measuring telescopes does not appear to be required for a space program. Although the oscillations were observed in a diameter measurement, the primary manifestation of the oscillatons is not a radius change but a change in the radiation intensity of the solar limb, i.e., a change in the limb darkening function. This has been demonstrated by simultaneous studies of diameter and radiation intensity measurements (Hill and Caudell, 1979; Knapp, Hill and Caudell, 1979). The properties of the radiation intensity in relation to solar oscillations have also been studied by Stebbins (1979), Brown (1979), and Brown and Harrison (1979).

3a. Properties of the Radiation Intensity

It has been possible by simultaneous diameter and radiation intensity measurements (Knapp, Hill and Caudell, 1979) to ascertain the spatial properties near the solar limb of I', the Eulerian perturbation of the radiation intensity associated with the oscillations observed in solar diameter measurements. The necessity of using simultaneous diameter and radiation intensity measurements to recover I' arises because of the techniques currently used to reduce the effects of seeing in the earth's atmosphere.

Samples of the results obtained by Knapp, Hill and Caudell, (1979) for I' are shown in Figures 1 and 2. This is the oscillating part of I at frequencies 0.415 and 0.511 mHz as a function of position. Note that the phases are functions of position. The Eulerian perturbation of I is chosen as the most useful representation of the results in designing the detector. This is the change in I observed at some fixed direction in space, not in some moving coordinate system such as with a Lagrangian pertubation.

The most striking feature of I', as shown in Figures 1 and 2, is the pronounced peak at the solar limb. The detection of the solar oscillations is made easier where the detector is designed to take advantage of this spatial property.

3b. An astrometric quality instrument

As shown by Stebbens (1979), it is not necessary to have an astrometric quality instrument to detect the low order solar oscillations. However, if the important properties of the radiation intensity I', as shown in Figures 1 and 2 are to be fully utilized and if it is desired to be able to study I' in more detail, a quantity sorely needed in the study of pulsation theory boundary conditions, then the constraint for an astrometric quality telescope cannot be relaxed.

It is noted that the astrometric quality of the instrument is one of considerble scientific value. However, the astrometric quality is required only in the measurement of one limb relative to a diametrically opposite one, not a measure of the diameter per se. The design that is under test at SCLERA is outlined in Figure 3 where the two appropriate images on the solar limb are imaged on one detector. The ground-based observations currently suggest a telescope for space use with a focal length on the order of 10 meters in order to match the CID array to the telescope plate scale.

3c. Detector

The applicability of Charge Injection Device (CID) for use as a self scanned imaging array for astronomical observations has been discussed by Aikens, Lynds and Nelson (1976). The advantages of random addresses and non-destructive readout suggested it's use for solar limb imaging. The 40μ pixel size for the General Electric TN 2200 camera provides a convenient scale of 80 x 80 arc seconds at the SCLERA astrometric telescope focal plane thereby matching the present 54 x 100 arcsecond raster scanned field. For ground based telescopes where seeing effects predominate, solar telescopes whose focal lengths exceed 10 meters would be required to insure that a sufficient portion of the limb had been imaged upon the CID detector chip for analysis. In space, however, the final edge definition depends more upon detector array quality, which we have attempted to study in the laboratory by means of imaging simulated solar limb targets. An interdata 6/16 computer was used to process bursts of ten digital frames generated by a General Electric TN 2200 camera and PA 2110A Interface unit. An edge definition scheme was used in which the inflection point was determined for each scan line, frame, and burst of frames with a resultant precision of ±0.2 microns in five seconds. These results confirm the utility of the CID camera as the second generation detector for high spatial resolution solar limb imagery.

Summary

To aid in continued study of solar oscillations from Earth and space based telescopes, a detector package has been described which extends existing observational techniques. This second generation detector images sufficient regions of opposing solar limbs to allow detailed investigation of the low order global oscillations over extended periods of time. The new data which the CID detector camera provides will directly support the understanding of the cyclic nature of the sun.

The authors wish to acknowledge the very important contribution of J. Knapp who kindly lent his preliminary data for figures 1 and 2 of phase and intensity vs solar radius. T. P. Caudell has made available his 1978 solar limb profile data in addition to very valuable discussions. All necessary computer programs to operate the CID camera have been generated by M. W. Bushroe.

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** SCLERA is an acronym for the Santa Catalina Laboratory for Experimental Relativity by Astrometry, a research facility jointly operated by the University of Arizona Department of Physics and by Wesleyan University.

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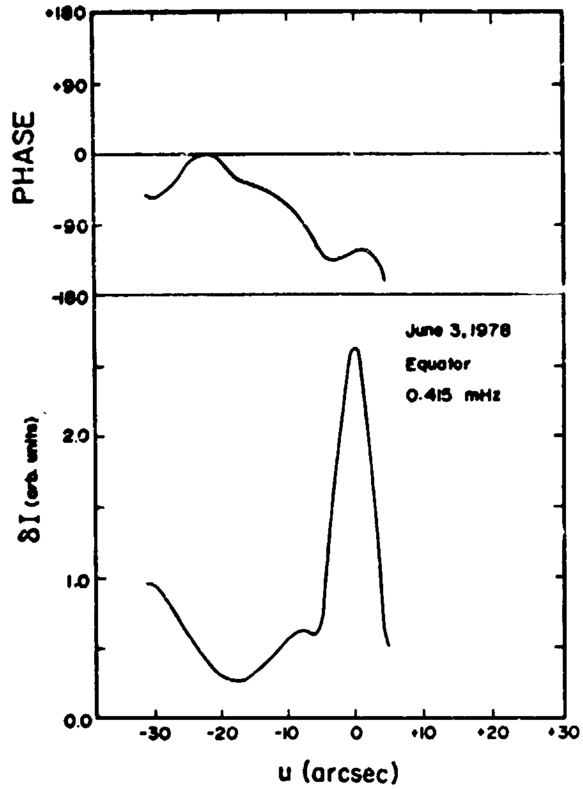

Figure 1

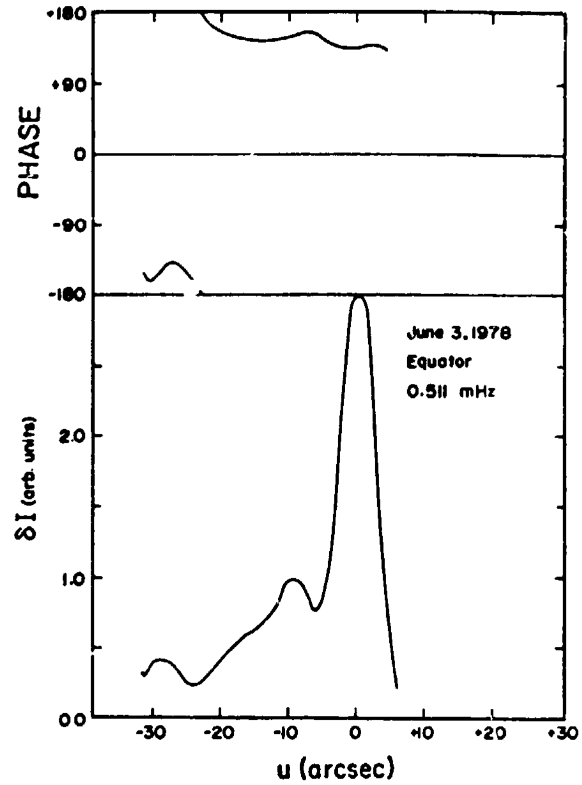

Figure 2

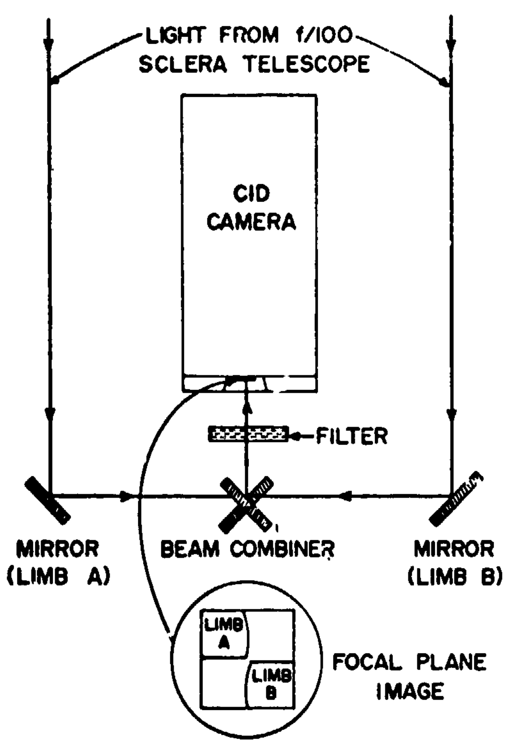

Figure 3

FIGURE CAPTIONS

Figures 1 and 2. Radial Dependency of Amplitude and Phase of the Eulerian Perturbation in the Radiation Intensity at 0.415 and 0.511 mHz respectively.

Figure 3. Optical Schematic for the Dual Limb CID Camera Detector System.

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THE MEASUREMENT OF GLOBAL SCALE SURFACE DYNAMICS

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Abstract

The SCADM mission implicitly contains a requirement for a fundamentally new type of satellite instrument: a very sensitive (~ 1 m s^{-1}), imaging velocity detector. This is needed to measure global oscillations and global circulation patterns, but the sensitivity requirement is so severe that it has not yet been met even with ground based instruments. In this presentation, the various possible sources of noise and other errors in such a device are considered, and the more detailed instrumental requirements are developed. This leads to the conceptual design of a "velocitygraph" that appears to achieve the necessary sensitivity and imaging capability within a resonable weight and volume.

I. Introduction

At the very heart of the Solar Cycle and Dynamics Mission there is a need to measure the surface motions of the sun very precisely. These observed surface motions are extraordinarily useful as diagnostic tools which can be used in a variety of ways to infer the structure and dynamics of the solar interior. The scientific questions that can be answered by this approach have been discussed by Gilman (1979). Here, we only need to summarize the different types of surface motions that can be observed and that bear directly on the problem of internal structure and dynamics:

1. differential rotation
2. Global eddies
3. The interaction of these two phenomena with each other and with solar activity
4. 5 min oscillations of all spatial scales
5. Longer period oscillations (the so-called global oscillations)
6. The evolution of all of these phenomena throughout the solar cycle

All of these effects should be observed with a basic accuracy of 1 to 10 ms^{-1} (Gilman, 1979).

There is a fundamental problem with this entire direction of research: this extremely high velocity accuracy of up to 1 m s^{-1} has never been attained before, not even with a ground-based instrument. Therefore it seems essential to confront the following basic questions: Is it even possible to build a space qualified "velocitygraph" with an accuracy of 1 m s^{-1}? If so, what is the best way to do it? It is the purpose of this contribution to begin the search for the answers to these two questions.

The approach that will be followed will be a "top down" consideration of the observational requirements first, then the technical problems to be expected. The critical technical problems should be identified as quickly as possible. Following this, the general types of spectral isolation devices will be considered with the intent of identifying the optimum type of instrument. Finally, a strawman instrument will be developed in more detail to see if it can indeed fulfill all the requirements. At such a preliminary stage, the analysis will have to be quite general, with many important details treated only in a very cursory manner. But the two basic questions will be answered and the critical problem areas will be identified.

II. General Considerations

A. Observational Requirements

The prime requirement is the above mentioned velocity accuracy of 1 m s^{-1} that is estimated to be necessary to detect global eddies and large-scale, low-frequency oscillations. This requirement can only be an estimate at this time because there is no real theoretical guidance as to what the expected amplitudes of these motions may be. There is also no empirical guidance because these motions have not yet been reliably detected. Still, it can serve as a very useful reference point against which instrumental capabilities can be measured.

The required spatial resolution is a very important parameter. There is no clear minimum resolution requirement with regard to any oscillatory mode, since these modes can be excited over the complete range of spatial wavelengths. A rough resolution requirement can be derived by requiring that an active region be at least crudely resolved so that any possible interaction between it and a global eddy can be detected. This is roughly 10 arc sec resolution. Of course, the maximum field of view must be the entire solar disk since the truly global effects are of paramount importance.

The time required to make one sample of the entire sun must be less than 2 minutes, preferably even less. Otherwise, the relatively large power present in the 5 min oscillations will be aliased into lower frequencies. An equally stringent requirement is that the total observing time be of the order of 5 days and the duty cycle be nearly 100%. This is necessary to resolve the individual oscillatory modes, as is being discussed elsewhere in this symposium (c.f., the contributions by Rhodes and by Brown).

In summary, one needs to make a velocity map of the sun, with about 200 x 200 grid points, every two minutes for 5 days, with each measurement being accurate to 1 m s^{-1}. It is important to note at this point that these requirements imply not only a high sensitivity to Doppler shifts, but also a high wavelength stability. Essentially, the wavelength of a solar absorption line must be known to 1 part in 3 x 10^8 over the entire field of view at any time for 5 full days!.

B. Technical Problems

In order to achieve such sensitivity and stability an impressive list of technical problems will have to be solved. It is well to begin making this list now, so that the individual items on it may be considered as soon as possible. Table 1 contains such a list. It is most certainly still incomplete at this early date, but it should contain the major problems. Most of the items on the list are self-explanatory, but several of them deserve further comment.

Calibration will be a major problem. Currently, most techniques measure ΔI in the wing of an absorption line at a fixed λ and calibrate the Doppler shift $\Delta\lambda = f(\Delta I)$ by measuring the line profile. But the line profile changes as a function of the motion, and anyway solar lines are not even symmetric. One must therefore confront not only instrumental calibration problems, but also the interpretation of a velocity from a line which is changing its profile as well as shifting.

The maintenance of wavelength stability for 5 days will be a major engineering challenge. It seems imperative that a wavelength standard, preferably a low pressure absorption cell, will have to be an integral part of any instrument, and that the observed wavelength of a solar line will have to be referenced to this standard as directly as possible.

The instrument will have to have a very wide dynamic range. The upper limit for this seems to be driven by the orbital line-of-sight velocity of the satellite, ~ ± 5 km s^{-1}, or a dynamic range of ~ 10^4. When this dynamic range is added to the requirement to make a 200 x 200 map of the sun every 2 minutes, it becomes clear that the data rate of this instrument will have to be very high. A minimum data rate, to transmit maps of Doppler shifts only, is ~ 10 k bits s^{-1}, continuous. In reality, several other parameters will probably also be mapped and transmitted, such as intensity in the line core and continuum, an asymmetry parameter, and so on. 10 k bits s^{-1} will be needed for each of these parameters. This data rate will have a severe impact not only on the telemetry system, but also on the experiment electronics and processing design.

Is there anything to be gained by merely listing the major problems, and not solving any of them? Yes, one important conclusion emerges directly from this list: The best spectral isolation device that is used to measure the Doppler shift would be one that is capable of measuring two complete line profiles (a solar line and a reference line) simultaneously and is capable of tracking the shift of each profile independently over a range equivalent to 10 km s^{-1}. This capability alone will make the solution of many separate problems on the list much easier. For example, an observed shift of the reference line will provide evidence of an instrumental wavelength drift and will provide an error signal to a servo wavelength stabilization scheme. Other examples come readily to mind.

C. Noise

Noise is an important consideration, and can enter into the experiment in subtle ways. Therefore, a few general remarks about it in passing are appropriate. One can always separate noise sources into three general categories; random, or "white" noise, low-frequency or 1/f or "red" noise, and band-limited or "monochromatic" noise. (When dealing with quantities that are a function of space and time, as this instrument will, it is understood that the frequency characteristics or "color" of noise sources must be applied to spatial wavenumbers as well as to temporal frequencies.) White noise sources are photon noise, detector noise and truly random solar motions. If these noise sources can be kept below 1 m s^{-1}, they will be absolutely negligible. The reason is that white noise power, by definition, will be spread evenly over the entire observed k-ω plane. Given the observational parameters listed above, the k-ω space will have the order of 10^7 resolution bins in it. Therefore, a total white noise power of 1 m^2 s^{-2} will result in a noise per k-ω bin of ~ 0.3 mm s^{-1}! This implies detectability of a 5 min oscillation with a total excursion of about one inch! Conclusion: white noise is not a limiting factor.

Band-limited, or "monochromatic" noise generally comes from instrumental flaws, and as such is an engineering "detail". An excellent real example of such noise

Table 1. Anticipated Technical Problems

How to make a single observation of $\Delta\lambda$ to one part in 3×10^8?

- What is the optimum spectral resolution?
- How to achieve sufficient photon statistics?
- Accurate calibration
- Measurement and interpretation of line profile asymmetries and variations
- Calibration of instrumental profile, including second order effects

Instrumental stability for 5 days

- Variation of line profile over the field of view
- Mechanical, thermal and electronic fluctuations
- Can passive stability be achieved, or must active servo techniques be used?

Spurious velocities of solar origin

- Solar rotation implies a requirement for wide dynamic range and small guiding errors
- Granulation, supergranulation produce low (temporal) frequency noise; require small guiding errors.

Data Throughput

- Optical throughput
- High speed electronic and digital processing
- Telemetry requirements

Detector Associated Problems

- Detector saturation
- Gain variations of array detectors

Orbit Associated Problems

- Need special orbit to get near 100% duty cycle
- Orbital LOS velocity is ~ 5 km s^{-1}. This requires very high dynamic range
- Weight, size, power limitations

can be found in the results of Rhodes et al. (1977), wherein a slight guider error coupled through the scanning motion into spatially band-limited noise at k = 1.1 mm. More to the point, one can expect for example that any satellite experiment will have an intense noise spike at the satellite period. This might not be considered noise as such, but the result will still be to obscure solar signals at this frequency. Furthermore, the spike will be so intense that it will generate sidelobes at other frequencies which will also function as noise.

"Red" or 1/f noise comes from two general sources: instrumental and solar. Any instrumental drift or non-periodic change of any kind produces red noise. Solar granulation, supergranulation and any other non-periodic motions produce red noise. All of these sources can be intense. Nothing can be done about the solar sources, so they will define the utlimate limiting sensitivity of any experiment, and that sensitivity will vary over the $k-\omega$ plane depending on the true spectral content of these sources. That sensitivity has not yet been reached in the interesting long wavelength region of the $k-\omega$ plane, so it cannot now be estimated reliably. In practice, instrumentally originated red noise has been the limiting factor in all measurements of solar oscillations to date. This can be seen graphically and directly in the results of Rhodes, et al. (1977) and Deubner, et al. (1979). In any experiment, this noise source can only be reduced by careful attention to instrumental stability. Conclusion: In the instrument considered herein, stability will be a critical technical problem.

D. Types of Spectral Isolation Devices

It is clear that the heart of this entire instrument will be the spectral isolation device. Is any one type of device clearly superior to the others? Table 2 lists the various general types and their advantages and disadvantages. It is of course possible to devise various modifications and combinations of these general types, so the simple categorization of Table 2 is valid to first order only.

All of the devices listed in Table 2 have at least one serious weakness. For two of the devices, the Fourier Transform Spectrometer and the Heterodyne Spectrometer, the weaknesses appear to be fatal. Filters are obvious candidates for a satellite instrument because of their small size and weight. But they must be constantly tuned in wavelength back and forth between the reference line and the solar line, as well as across the profile of the solar line. Each step of this tuning process must be controlled to one part in 3 x 10^8. This introduces undesired complexity and still more control problems. Furthermore, filters are the most difficult of all the types of devices to control by the very reason that they are so small. The required mechanical tolerances are literally of atomic dimensions! As an order of magnitude example, consider a Fabry Perot filter with a cavity length of 1 cm. (A realistic device of this size would have a resolution of $\sim 2 \times 10^5$ in the visible spectrum, more than sufficient to measure a crude solar line profile.) The spacing, flatness and parallelism of the plates of such a filter would have to be controlled to a linear dimension of 1/3 Å. Clever design could certainly relax this requirement to some extent, but it would always remain as a major weakness of filters. Filters can be used as dispersing devices, thereby eliminating the need for tuning. The classical ring spectrum of a Fabry-Perot is perhaps the best known example of such a mode of operation. However, this sacrifices throughput which would have to be compensated for by making the filter larger. Furthermore, the atomic mechanical tolerances mentioned above remain.

By process of elimination then, one is left with the grating spectrometer, the largest, heaviest and technically least sophisticated device of all. It should however be noted that all previous ground-based velocity observations which have led to k-ω analyses have been made with grating spectrographs. There are reasons for this. The main reason is that the most citical variable of all, wavelength, is presented to the detector instantaneously and unmultiplexed. This immediately eliminates tuning problems, electronic problems associated with demultiplexing, and time-delay problems. Furthermore, a second variable, one spatial dimension, is also passed simultaneously through a grating spectrometer, enabling the array detectors currently being developed to be utilized to their full potential. Of the viable candidates, only the grating spectrometer possesses all of the desirable characteristics of a spectral isolation device that were described in Section IIB.

The usual low throughput disadvantage of gratings can be removed for this application because high spatial resolution is not required. Given a moderately large grating with spectral resolution far greater than needed to measure a crude line profile, the entrance slit of the spectrometer can be opened much wider than its theoretical resolving limit, thereby achieving increased throughput at the expense of the unneeded spatial and spectral resolution. It remains to be seen if such a concept will indeed work out and fit into a package of at least moderate size.

Table 2. Types of Spectral Isolation Devices

1. Filters

advantages:	small, light weight, high throughput
disadvantages:	must tune over λ. Every tuning step must be controlled to 1/3 x 10^{-8}. Mechanical tolerances are of atomic dimensions.

2. Filters used as dispersing devices

advantages:	small, light weight, no tuning required
disadvantages:	low throughput, instrumental profile is a function of wavelength, severe mechanical tolerances.

3. Fourier Transform Spectrometer

advantages:	small, light weight, high throughput, λ multiplexed
disadvantages:	the need for de-multiplexing λ puts an intolerable burden on electronics, severe mechanical tolerances.

4. Heterodyne Spectrometer

advantages:	small, light weight, can achieve full spectral resolution and stability.
disadvantages:	throughput is intolerably low.

5. Grating Spectrometer

advantages:	wavelength and one spatial coordinate are transmitted simultaneously and unmultiplexed, mechanical tolerances are of the order of the wavelength of visible light.
disadvantages:	low throughput, large size.

III. Strawman Grating Spectrometer

A. Optical Description

We can now develop the main features of a complete "velocitygraph" based on a grating spectrometer that is used in the "high throughput - low resolution" mode. We begin by setting the desired observational parameters in more detail. The aperture of the telescope is then set by the desire to count enough photons to reduce photon noise below 1 m s^{-1}. The spectrograph is then matched to the telescope.

An angular resolution of 8 arc sec is adopted. This results in 250 spatial resolution elements across the sun, a number that is well matched to the size of many two dimensional detectors. A spectral resolution of .080 Å is sufficient to record a crude line profile. However, adjacent elements of an array detector can simultaneously count photons throughout the entire line.

Straightforward calculations show that, in order to measure a Doppler shift of a moderately deep solar absorption line corresponding to 1 m s^{-1}, about 4×10^8 photons must be counted. The entrance slit of the spectrometer must be scanned across the sun ($\approx$ 250 resolution elements) in 100 s or less. So the required photon count rate is $N = 4 \times 10^8 \left(\frac{250}{100}\right) = 10^9$ photons s^{-1} per spatial resolution element. Taking the resolution element to be 8 arc sec, a wavelength interval of .032 Å (4 spectral resolution elements) and reasonable estimates of the transmission of each optical element and detector efficiency, this photon rate can be achieved with a telescope 15 cm in diameter.

The spectrograph is sized by matching its throughput to that of the telescope. This leads to the relation:

$$D_{spec} = \frac{\Delta\,\theta\ (\text{arc sec})}{103\ \Delta\lambda\ (\text{Å})}\quad D_{telescope} \qquad (1)$$

For the above $\Delta\theta$ and $\Delta\lambda$, $D_{spec} \approx D_{telescope}$! The apertures of the spectrograph and telescope can be identical; the telescope serves then only to provide a focal plane at the entrance slit of the spectrograph. A grating of dimensions 15 x 30 cm is large enough to satisfy the throughput requirement. The theoretical resolution of a grating this size is .009 Å, therefore the instrumental profile will be dominated by the finite width of the entrance slit.

The focal length is a very critical parameter. It is set by the need to image one angular resolution element onto one detector resolution element. Taking a typical detector element size of 50 μm, the resulting focal length is 1.5 m. (This implies an f ratio of 9.5 which is faster than common grating spectrographs of this size. Therefore care in the optical design and fabrication seems to be indicated in order to reduce aberrations to an acceptable value.) Given the need for a telescope and a spectrograph, each with a focal length of 1.5 m, and the possibility of folding at least the telescope optical path, it seems fairly safe to predict even at this early stage that the entire optical assembly can be contained in a package of 3 m length, perhaps 4 m at the most. Conclusion: It is indeed possible to construct a grating spectrometer device with sufficient throughput and spectral resolution that is still small enough to be flown on the SCADM mission.

B. Detector Requirements

The ideal detector is a CID or CCD array with about $\approx$ 256 x 256 diodes on 50 μm centers. However, rather severe requirements are placed on such a detector and its amplifier. As discussed above, in order to achieve photon statistics sufficient for sensitivity of 1 m s^{-1} it is necessary to detect $\approx 4 \times 10^8$ photons on four diodes. Since $\approx$ 250 spatial elements must be scanned in 100 s or less, then 10^8 photons must be counted by a single diode in 100/250 = .4 s. If the array is read out at a rather standard rate of 30 Hz (i.e., 12 readouts per single observation), then two severe requirements result: 1) Each diode must be able to store a charge of $\approx 10^7$ photoelectrons without saturating. 2) The amplifier must operate at a rate of 2 MHz with a noise equivalent charge of less than $\sqrt{10^7} = 3 \times 10^3$ electrons. These two requirements can be traded off directly against each other, but they both already challenge detector and amplifier technology. Present array detectors typically saturate at 10^6 photoelectrons or less and present amplifiers operate at $\approx 2 \times 10^5$ Hz. Since both these parameters are an order of magnitude too low, it is clear that the detector/amplifier combination represents a critical problem area. To state this problem another way, the throughput limit of this instrument is at the detector/amplifier stage, not in the optics.

There are schemes by which this problem can be alleviated. For example, one scheme recognizes that, of the 256^2 diodes in the array, the outputs from only a small fraction of those are really of interest and need be amplified etc., namely only those columns of diodes that lie in or near the two spectral lines of interest. This amounts to about ten columns for each line, or a total of 20. The other 236 columns sample only uninteresting continuum. If the output from these 20 columns of diodes can be stored for later amplification, then the required amplifier rate is reduced by an order of magnitude. Another possibility is to increase the saturation charge of the detector by increasing the area per diode. If the diode spacing is increased from the nominal 50 μ m to 150 μ m, the saturation level is 9 times higher. This would require optical magnification of some kind near the focal plane though. Clearly, important details remain to be worked out in this area.

IV. Summary and Conclusions

The broad and cursory tone of this paper is intentional. Its purpose is to stimulate thought and discussion by pointing out problem areas and possible solutions, and not to present any given solution or total package in great detail. Nevertheless, a few general conclusions already appear to be fairly firm. First, the two questions posed in the introduction can be answered: The construction of a satellite based 1 m s^{-1} "velocity-graph" does appear to be feasible. A grating spectrometer appears to be the best type of instrument for the job. Beyond these two statements, two technical poblem areas can be identified as being the most critical: 1. The stability of the instrument is more critical than its noise level, and will probably set the ultimate sensitivity level. 2. The throughput limit of the entire instrument is at the detector/amplifier combination. The capacity of the detector and the noise of the amplifier are critical technical problems.

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N80-17956 D/2

Observational Requirements for Measurements of Solar Rotation Inward to the Base of the Convection Zone

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As we have already heard earlier in this symposium, the acquisition and analysis of observational data concerning the dynamical state of the solar interior will be crucial for improving our understanding of the solar activity cycle. Among these data will be measurements of the rate of rotation at various depths in the solar interior and of temporal changes in the rotation.

This afternoon I hope to convey the following three points: first, it is now possible to measure the absolute rate of the sun's rotation (in meters per second) below its visible surface over the outer 3% of its radius with ground-based equipment; second, the theory of this technique has now been developed to the point where it is potentially possible to measure rotation inward to the base of the solar convection zone; and third, such deeper rotational measurements, extending from 3% inward to 25-30% of the sun's radius can only be obtained from a space-borne instrument which is not subject to the normal earth-based day-night observing cycle.

To begin, it is the existence of the non-radial acoustic (or p-mode) oscillations of the sun which permits the measurement of sub-photospheric solar rotation. The first figure shows the most recent observational confirmation of the existence of the p-mode oscillations. This figure is a grey-level display of a diagnostic diagram, or two-dimensional (k_h - ω) power spectrum. This spectrum was obtained from a continuous 11-hour observing run on the McMath Telescope at the Kitt Peak National Observatory. It was obtained on 15 April 1979 with the assistance of Drs. Jack Harvey and Tom Duvall. It shows the concentration of observed power into many distinct ridges. These ridges are distinct functions of the horizontal wavenumber (running across the spectrum) and temporal frequency (running vertically).

Theoretical eigenmode analysis shows that these ridges of observed power are due to non-radial p-mode oscillations. It is these power ridges which permit the measurement of solar rotation with the oscillations. This is accomplished by guiding the telescope being used on the limbs of the sun and then letting the sun's rotation carry the pattern of oscillating motions through the telescope's field of view. observations are made in this manner, the p-mode ridges are systematically shif[illegible] in frequency. For example, in this figure he upper set of ridges can be seen at higher absolute frequencies than the lower set of ridges, which in turn have been shifted to lower absolute frequencies. (Since the origin of the spectrum in the figure is in the middle of the left-hand axis, positive frequencies increase upward at the top while negative frequencies increase downward at the bottom.)

Rhodes, Deubner, and Ulrich (1979) have recently shown that the amount of frequency splitting which is introduced in corresponding ridges in the two parts of the spectrum by the rotation is proportional to both the horizontal wavenumber, k_h, and the rotational velocity, V_{rot}. By measuring both the frequency splitting and the horizontal wavenumber at various places in the spectrum, one can calculate the rotational velocity (or velocities) directly.

The exciting aspect of making these measurements at different depths below the photosphere comes about because the individual p-mode waves are sensitive to rotational influences at different depths. This fact is illustrated in the second figure. In this figure I show an expanded portion of the theoretically-predicted p-mode spectrum for long wavelengths (small k_h). In this figure the theoretical p-mode ridges are shown as the light solid curves which run diagonally across the spectrum and which are labeled P_0 through P_{14}. The heavier solid lines which are running more vertically are contour lines which show the locations of those wavemodes which have the same effective depths. The scale of the depth contours is shown adjacent to them and is labeled in fractions of the sun's radius. Clearly, much of the spectrum is sensitive to rotation at relatively shallow depths (i.e., depths near 1.0 R_Θ), while the deeper-going portions of the spectrum are crowded together at low wavenumbers. As of this time, rotational observations have only been obtained with the p-modes for the outer 3% of the solar radius. The results of these ground-based observations are contained in Deubner, Ulrich, and Rhodes (1979).

The interesting, deeply-penetrating modes are precisely those which are the most crowded together in the spectrum and hence are the most difficult to separate observationally. In addition, the expected frequency splitting due to rotation is much smaller for those modes since k_h is so much smaller than for the photospheric modes. These reasons indicate that the deeper-going modes must be observed from space. This conclusion will be demonstrated in the next few figures.

In Figure 3 I have expanded the theoretical power spectrum even further in order to demonstrate the fact that the p-mode ridges are not really a set of continuous ridges as indicated in Figure 2. Rather, the p-modes are spherical harmonics, one for each value of ℓ, m, and n, and the observed ridges are merely collections of these discrete modes. To measure the rate of rotation for the deepest modes, the individual ℓ values must be resolved. However, from any observing location on the earth the effective horizontal wavenumber resolution is limited by projection effects and is insufficient to spatially resolve these modes. In particular, for the longest practical baseline on the sun of one solar radius in extent, each horizontal wavenumber bin in the resulting power spectra will contain six different sets of ℓ modes. This degeneracy is illustrated in Figure 3 where the vertical lines denote the boundaries of the individual wavenumber bins for such a run. The complete set of p-modes which would lie in bin #4 is shown at the right-hand side of the figure as a vertical series of sp''es.

Clearly, there is a problem in the resolution of the individual p-modes in this part of the spectrum. Since the measurement of the rotationally-induced frequency shifts is based upon the identification of matching modes in the positive- and negative-frequency portions of the power spectrum, such confusion in the identification of corresponding modes makes the measurement of this splitting very difficult. The splitting can only be measured with an observing run of sufficient duration that the individual ℓ values are resolved in temporal frequency within each wavenumber bin. Such individual mode resolution is necessary in this part of the power spectrum because the magnitude of the induced frequency shifts will be less than one frequency resolution bin width.

To illustrate the observational requirements necessary for resolving individual modes, I have computed a series of synthetic power spectra for the six p_5 and six

p_6 modes located between ℓ values of 19 and 24 in Figure 3. Figure 4 shows part of the power spectral slice for wavenumber bin #4 which resulted from a simulated continuous solar viewing run consisting of 2048 measurement frames each lasting 90 seconds and having a total duration of 51.2 hours. For such a two-day run you can see that the individual ℓ values were resolved. On the other hand, when I simulated a ground-based data string consisting of a 12-hour observing day followed by a 12-hour dark night, a second 12-hour day, a second 12-hour dark night, and a short 3.2-hour data segment (so that the total length was 51.2 hours), the spectrum shown in Figure 5 resulted. This ground-based simulation shows clearly that the sidelobes introduced into the power spectrum by the day-night observing cycle make the identification and measurement of these p-modes impossible from the ground. The situation which resulted for a more typical 8-hour observing day followed by a 16-hour dark night is illustrated in Figure 6. This figure shows that such a situation is even worse.

Finally, Figure 7 is a simulation of a 51.2-hour observing run obtained from an equatorial-orbiting satellite having roughly a 67% duty cycle. Again, the individual p-modes are visible; however, in this case the sidelobes introduced by the observing window are hidden within several of the simulated solar spikes. The presence of sidelobes within the p-mode spikes will alter the frequencies that are determined for those spikes and will alter their estimated amplitudes. Such frequency errors will in principle introduce errors into the rotational-velocity determinations. The details of how much these satellite data gaps affect the rotation measurements are currently being investigated numerically. Certainly, such satellite data will be a vast improvement over what is available from the ground even if continuous solar viewing is not available in the near future.

In summary, I believe I have demonstrated that measurements of solar rotation inward to the base of the convective zone will require the acquisition of several day-long observing runs from a space-borne instrument.

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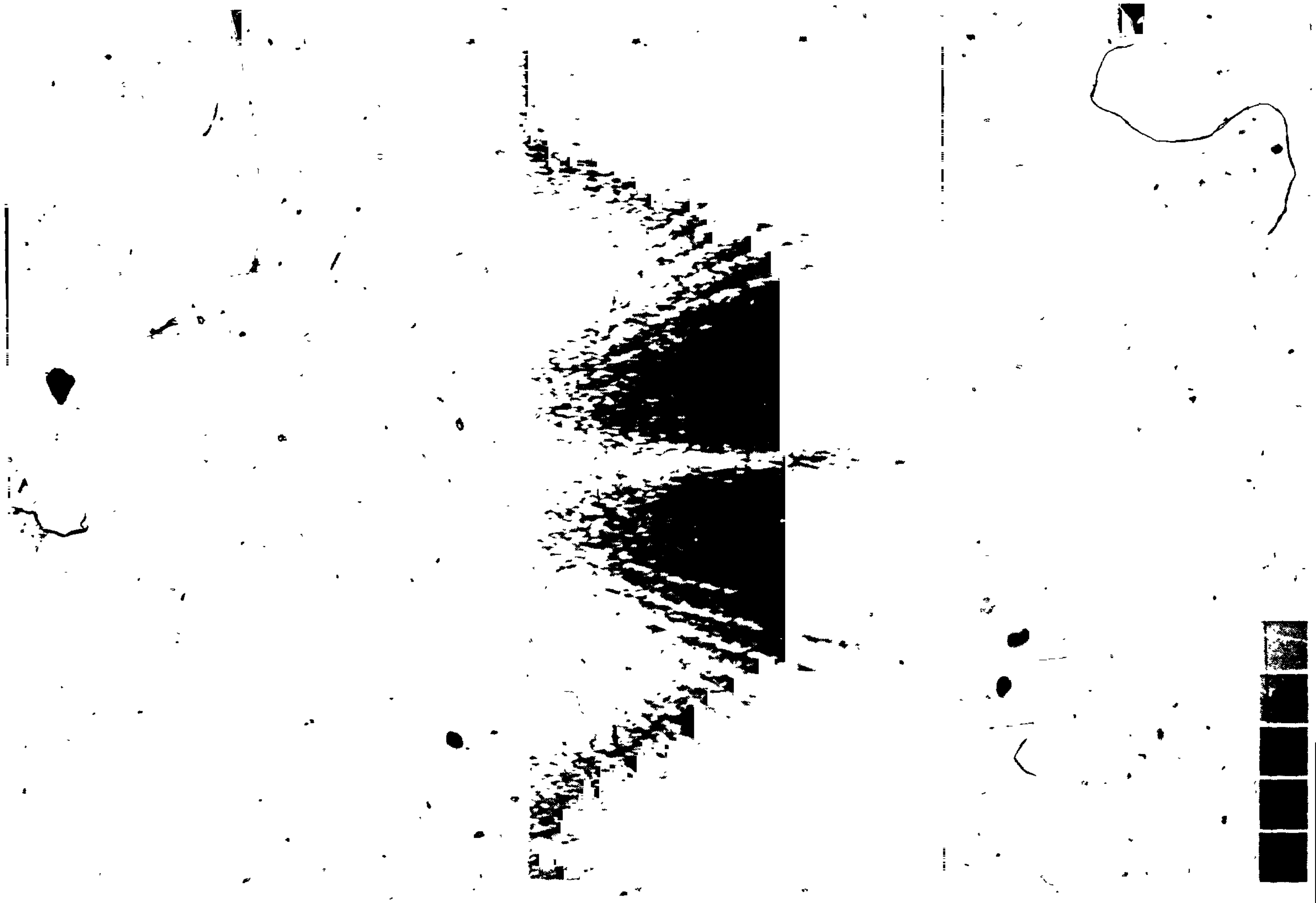

Figure 1. An observational two-dimensional (k_n - ω) power spectrum. Horizontal wavenumber increases from left to right, while temporal frequency runs along the vertical axis. The frequency is zero at the midpoint of the frequency axis and increases upward for positive frequencies (i.e., the top half of the spectrum) and increases downward for negative frequencies (the bottom half). The p-mode oscillations are the curved ridges of concentrated power. The spectrum shown is the result of an 11-hour observing run at the Kitt Peak National Observatory.

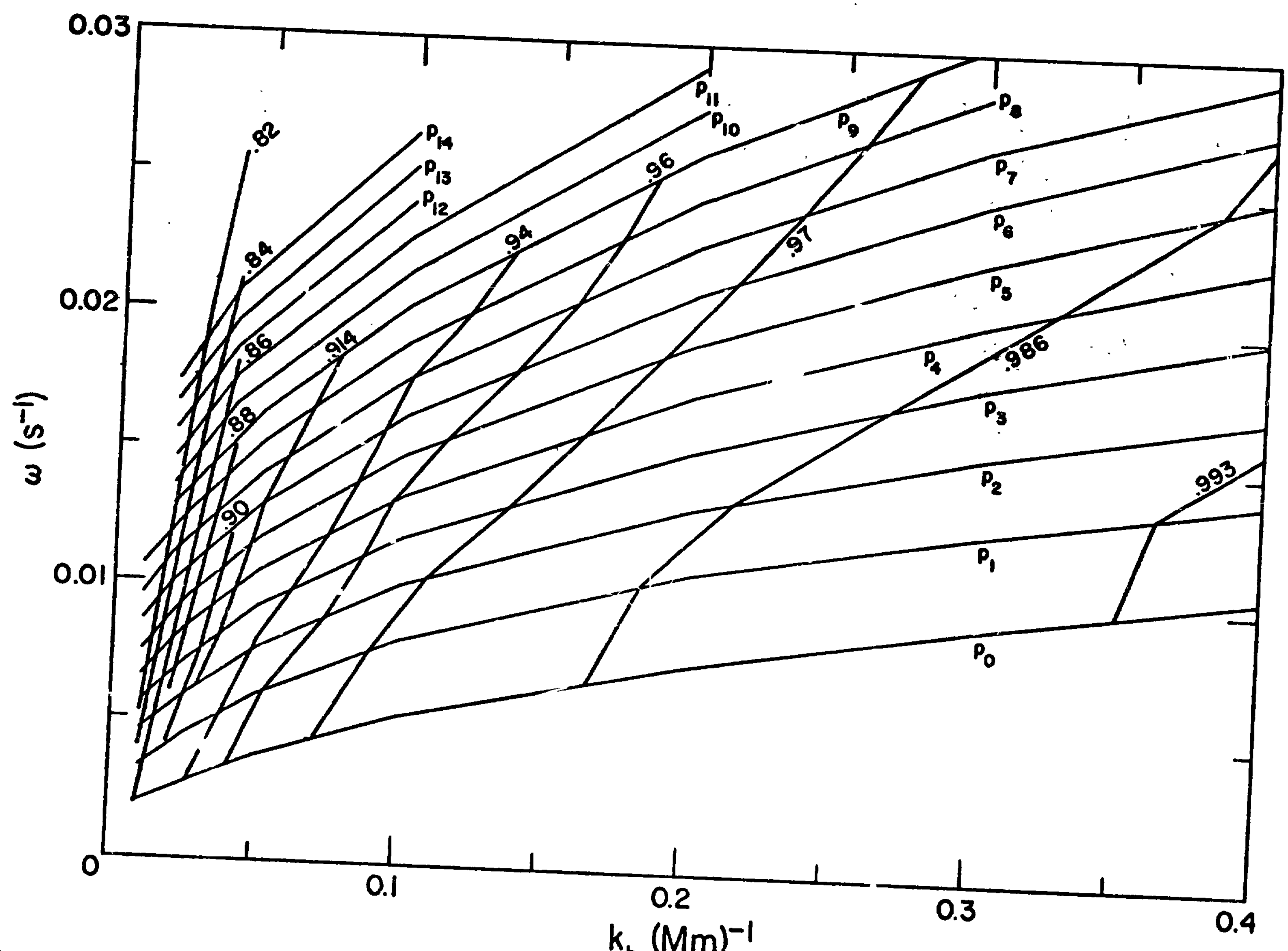

Figure 2. The long-wavelength (low k_h) portion of the theoretical p-mode eigenfrequency spectrum. The light curves are p-modes p_0 through p_{14}. The diagonal solid lines are contour lines showing those modes having particular effective depths to rotation. The scale of the effective depths is shown in fractions of the solar radius. The deepest-penetrating modes are those in the upper-left portion of the figure.

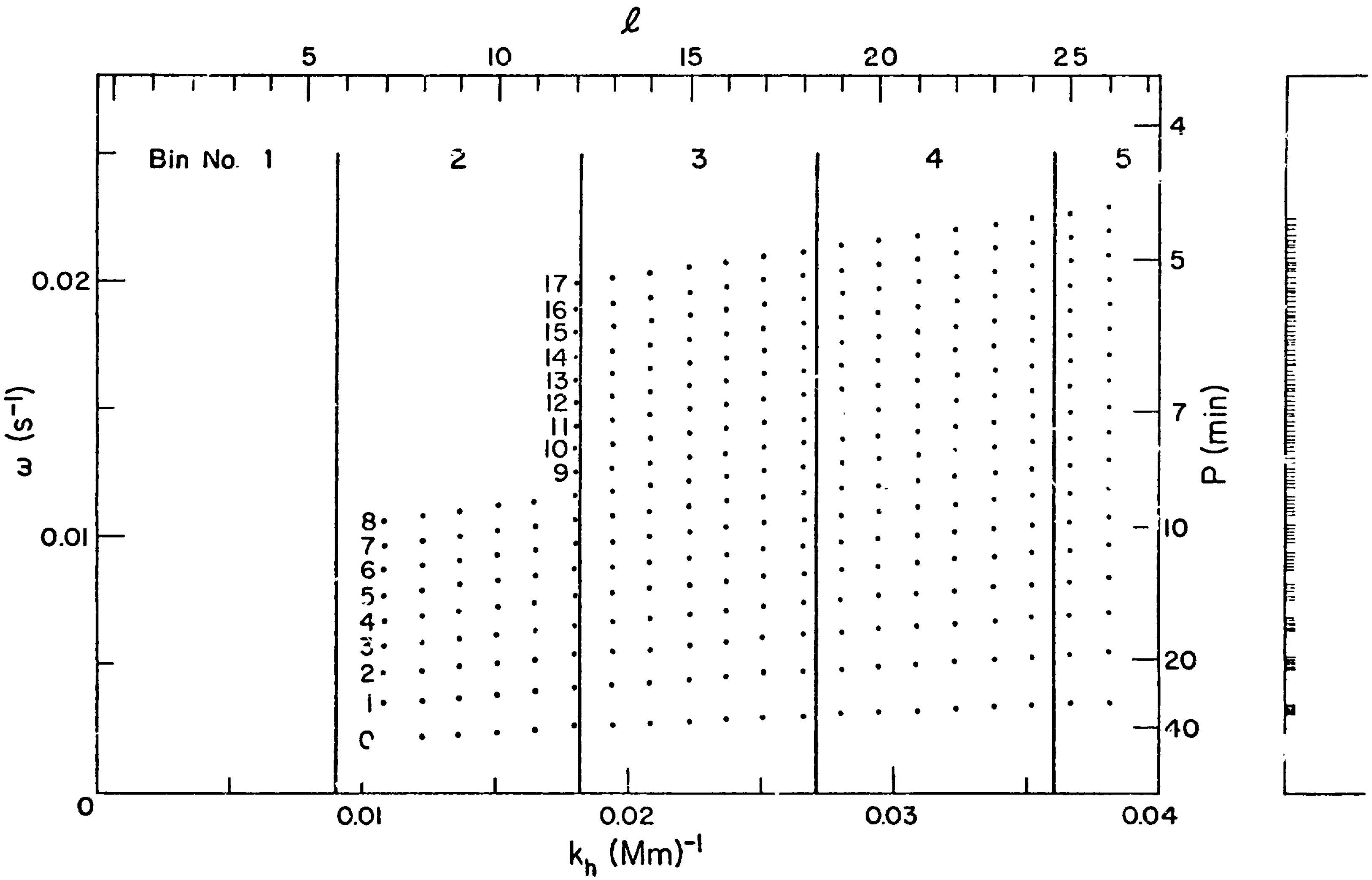

Figure 3. The extreme low-wavenumber portion of the eigenfrequency spectrum. The discrete nature of the p-modes is illustrated here, with one p-mode for each value of spherical harmonic degree, ℓ. The horizontal-wavenumber bins attainable from a single observing location are shown as the solid vertical lines. This shows that six discrete sets of p-modes lie within each resolution bin. The set of p-modes within bin #4 is plotted as the vertical strip of spikes at the right side. These modes can only be resolvable in temporal frequency with a long-duration set of observations.

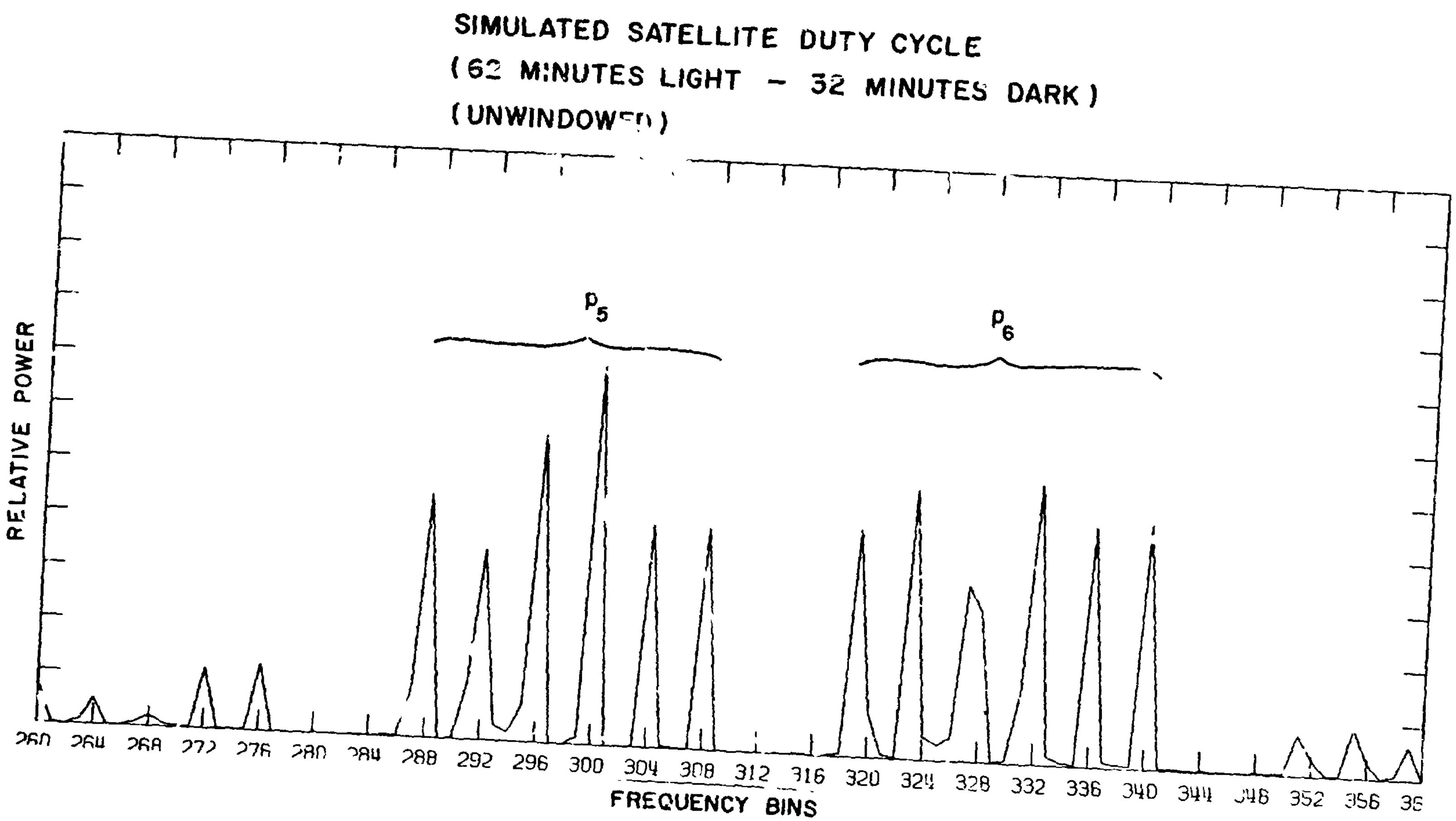

Figure 4   A synthetic one-dimensional (ω) spectrum generated from a simulated satellite experiment located in a sun-synchronous (continuous solar viewing) orbit. The spectrum contains the six p_5 and six p_6 modes illustrated in k_h bin #4 of Figure 3. A continuous data set consisting of 2048 90-second velocity samples was used to generate this spectrum. Thus, a run having a duration of 51.2 hours is needed to resolve these p-modes in ω.

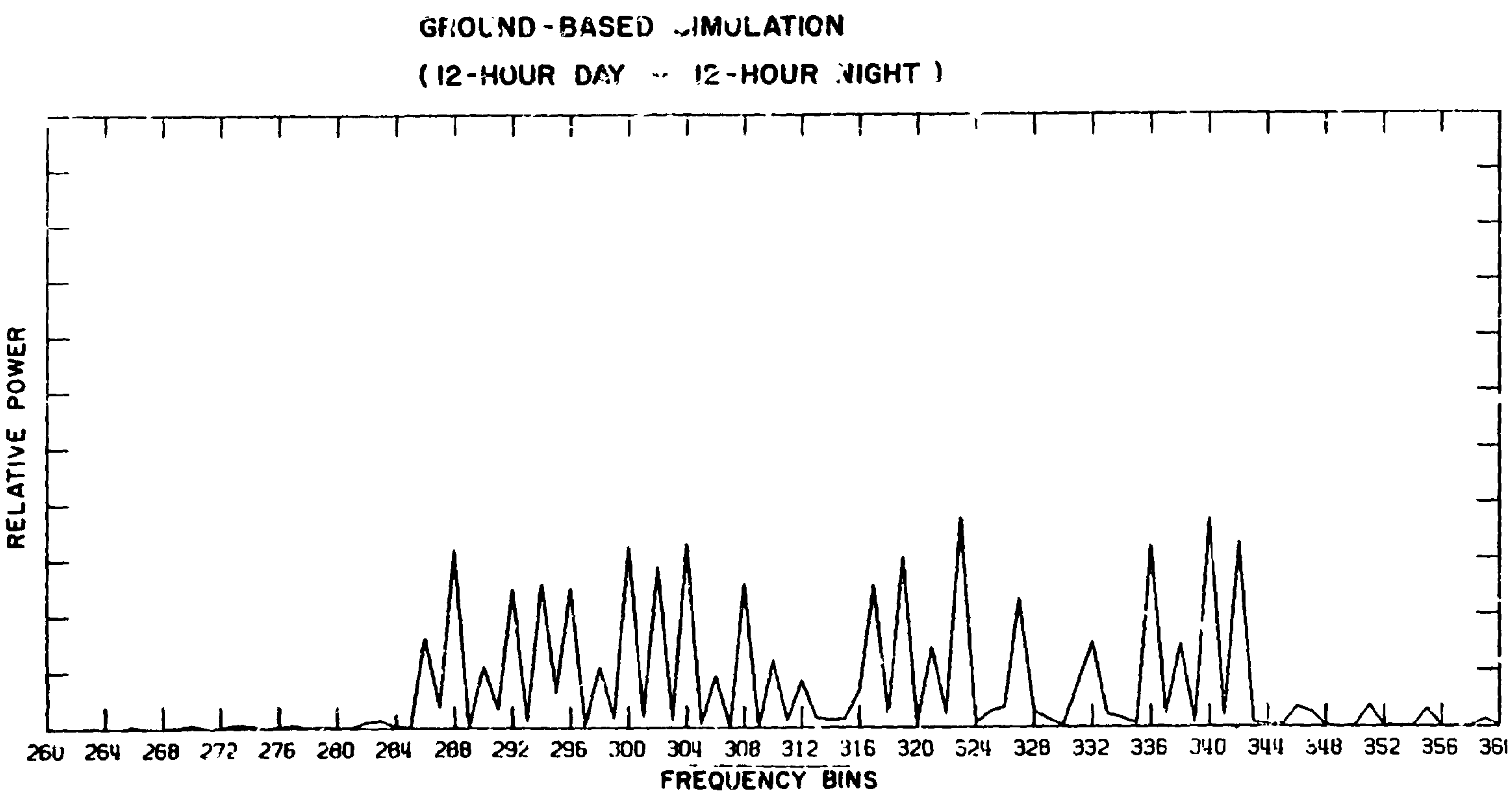

Figure 5. A synthetic power spectrum generated from a simulated ground-based observing sequence in which several days' worth of data have been stacked together. The data string used here consisted of one 12-hour (480-sample) observing day followed by a 12-hour dark night containing no data, a second 12-hour day, a second 12-hour night, and a 3.2-hour segment for the total of 2048 measurements. The total duration of the data string was identical to that used in Figure 4. The same assumed p-mode amplitudes were used as input to both spectra.

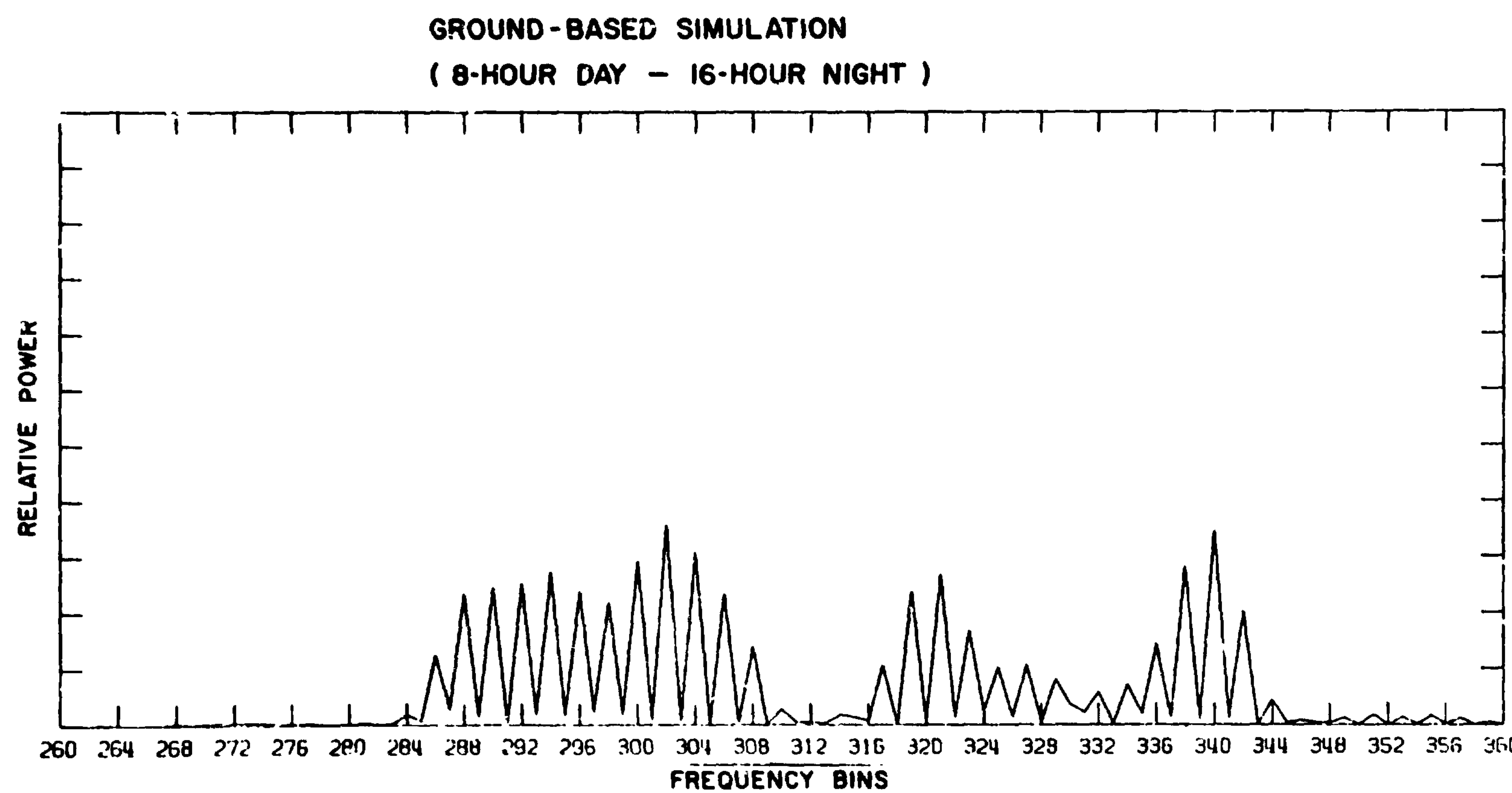

Figure 6. A synthetic power spectrum generated from a simulated ground-based observing sequence consisting of an 8-hour (320-sample) observing day followed by a 16-hour (640-sample) night, a second 8-hour day, a second 8-hour night, and a 3.2-hour segment. This spectrum was computed since the acquisition of continuous ground-based data for 8 hours is more likely than it is for 12 hours. The individual p-modes are completely unresolved in this spectrum.

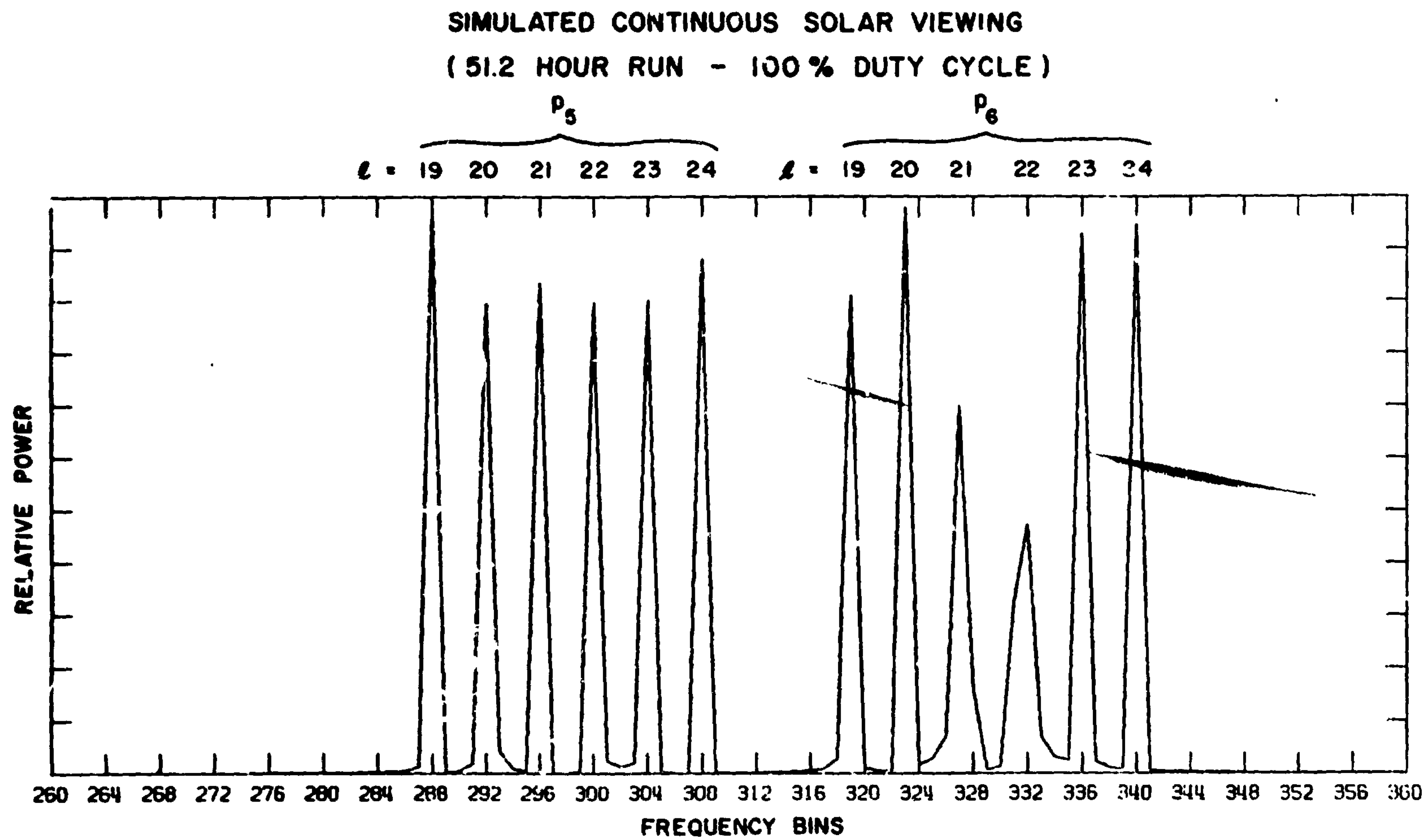

Figure 7. A synthetic power spectrum which resulted from a 51.2-hour observing run obtained with a simulated equatorial-orbiting earth satellite. The duty cycle used here was a series of orbits each containing 62 minutes of measurements followed by 32 minutes of darkness. The observing window had roughly 67 percent coverage. This observing window introduced sidelobes in the power spectrum which were mostly located within the same frequency bins containing other p-mode spikes. The effect of these sidelobes is to introduce errors in frequency determination for the p-mode peaks. The actual amount of frequency error introduced in this way is currently being investigated.

QUESTIONS AND COMMENTS

QUESTION BY: N. Sheeley, NRL

DIRECTED TO: E. Rhodes

QUESTION: Exactly what physical picture of the surface velocity field do you associate with the observed ridge pattern in the (K, ω) plane? For example, how does your mental picture differ from the one that would be obtained from other hypothetical patterns such as concentric circles about the point

$[(1000 \text{ km})^{-1}, 2\pi/300 \text{ sec}]$?

ANSWER: An instantaneous velocity snapshot of the solar p-mode, or pressure mode, oscillations in the photosphere is contained in Rhodes, Ulrich, and Simon (1977). This velocity picture has the appearance of a grid of randomly-distributed upwelling and downflowing cells. This pattern is the result of the superposition of an enormous number of spherical harmonics, each having a different horizontal cell size. The oscillatory gas velocity at every location across the solar surface is predominantly radial and not horizontal. That is, the term "non-radial p-mode oscillations" refers to the horizontal pattern of upward-and downward-flowing cells and not to the direction of the velocity itself. Each individual p-mode wave has associated with it a characteristic frequency and horizontal cell size. Some are zonal harmonics, others are sectorial harmonics, and still others are tesseral harmonics. Graphical illustrations of tesseral harmonics are contained in Kraut (1967) and in my thesis (Rhodes, 1977). The alternating pattern of radial velocities for such a mode is apparent in these figures. It is the superposition of patterns such as these which results in the instantaneous photospheric velocity field.

The reasons there were ridges in the k_h-ω spectra I displayed rather than circles were the following: first, in the two-dimensional power spectra the velocity observations had been filtered so that information was only shown for eastward-and-westward-propagating sectorial harmonics. In contrast to tesseral harmonics, sectorial harmonics look like orange slices or the alternating stripes on a beach ball. The width of each of these stripes (i.e., the horizontal wavelength of the pattern) is inversely proportional to the horizontal wavenumber, k_h. Second, the operation of the resonant cavity which traps the p-mode oscillations in the sun is like an organ pipe (i.e., there is a fundamental mode for each wavenumber and a series of higher-frequency harmonics). The depth of the inner reflecting boundary of this cavity varies with k_h and ω in just such a way as to produce a diagonal ridge for the fundamental mode (since a deeper

ANSWER:
(Continued)

pipe implies a lower frequency and vice versa). This cavity also produces parallel ridges for the overtones. A schematic cross-section of the resonant cavity is shown in Ulrich (1970) for a few modes.

It is the mathematical form of the dispersion equation for the p-mode waves which combines with the radial stratification of the solar atmosphere to result in the series of ridges in the k_h-ω diagrams. Circles would not be expected because they would not be compatible with the acoustic wave equations. On the other hand, if the velocity data had not been averaged to reveal only sectorial harmonics, a three-dimensional (k_x, k_y, and ω) power spectrum would have resulted. In such a spectrum the p-mode tesseral harmonics would result in a series of concentric circles at each single temporal frequency, ω. Thus, circles would result from a 3-dimensional analysis, but not from the 2-dimensional analysis discussed above.

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-13

A Sunspot Periodicity and the Solar Rotation

by

N80-17957

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Abstract

A least-squares power-spectrum analysis of 122 years of Zurich daily sunspot numbers has yielded a statistically significant peak at 12.0715±.002 days period. This feature at 11.685 days (sidereal) of the sunspot spectrum may be associated with the peak at 12.22 days(sidereal) which Dicke(1976) found in his oblateness data, and may be attributed to the sun's core if it rotates at either 12.0715 days or 24.1430 days period(synodic). A more recent, but different,analysis by Shapiro has not added further statistical support for this peak, although a moderate unresolved peak at this period might be consistent with the reported findings. It is suggested that spacecraft observations combined with correlative analysis of solar surface features between eastern and western hemispheres could further reveal a basic core periodicity. Further, a Dicke type space oblateness experiment could provide better photospheric observations than a ground instrument.

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I. Introduction

Considerations of a fast rotating solar interior began with Newcomb(1895) when it was realized that an oblate sun could influence Mercury's orbit and remove the perihelion problem in the same way that a massive inner planet Vulcan could. Dicke(1964) renewed these considerations and suggest. the solar core rotation period might be a half to two days.

Dicke and Goldenberg(1967) observed t . oblateness of the sun and found that during 1966 the solar oblateness was $4.51 \pm 0.34 \times 10^{-5}$. This oblateness was considerably larger than the turn of the century observations suggested, although observer bias and atmospheric distortion may account for this disagreement. Hill and Stebbins(1975) observed a solar oblateness in agreement with a core rotating with the surface 25 day (sidereal) period. Dicke(1976) points out that the 1966 sun may not be the 1973 sun.

Kraft's(1968) observation led Durney(1972) and Sakurai(1972) to show that, in its early history, the sun rotated 65 times its present surface rate. Dicke(1974a) and Sakurai(1975) review the subsequent history of the solar rotation. It was noted by Schatten(1977) that solar core contraction could lead to a more rapid solar rotation than one would otherwise calculate. A slow solar rotation was also possible, depending upon past solar history. Wolff(1976), based upon alignments of numerous periodicities in the sunspot power spectrum, found a 25.8 day "basic" rotation period for the entire solar mass. Other authors have also found different basic periodicites from solar activity parameters but usually did not associate these rotation rates with a fundamental core period.

Leighton's (1969) dynamo model of the solar activity cycle allowed a variety of internal rotation boundary conditions. To agree with the observed activity cycle, Leighton stated "it seems likely that the actual solar cycle is governed principally by the interation of a radial gradient of angular velocity with the radial field." He also found the best fit with "the interior rotating faster than the exterior."

A value for his rotation parameter corresponding to a velocity differential of 4 radians per year at the equator near the base of the convection zone seems to fit Spoerer's law best. If too fast an interior rotation is assumed , corresponding to Dicke's(1964) model, a problem of "sheets" of oppositely directed field arises.

Dicke furthered our understanding of the solar rotation by delving into a subject usually treated expeditiously. He analyzed his "noise". Based upon "enigmatic' fluctuations in the diagonal component of the solar oblateness observations of 1966 (Dicke and Goldenberg,1974), Dicke(1976) interpreted those signals as an ellipsoidal distortion tilted about 45 degrees from the solar rotation axis rotating rigidly with a period of 12.22 $\pm$ 0.12 days (sidereal). The interpretation required a complicated coordinate analysis as the observing instrument measured the solar diagonal component relative to the earth's north celestial pole. The diagonal component is basically the amount of light near 45° in the NE-SW quadrants of the sun above a certain radius minus that in the NW-SE quadrants. The original fluctuating signal was a complex structure containing a 25.67 day enigmatic periodicity diagonal component fluctuation, in a time T/2 later it will be on the NW limb and it should introduce a negative distortion.

Because this did not appear to be the case(Dicke,1974b) the fluctuations were enigmatic. Dicke(1976) reasoned that, as the position angle, P, of the sun changed from about -24° to +24° during the course of the experiment, often P was appreciably non-zero. Thus the sun was tilted with respect to the earth's axis and his instrument. Therefore, when P was 15° on August 13, for example, a blip appearing in the NE limb viewed at 45° would be near an angle of 30° from the apparent polar axis. When it rotated to the NW quadrant it would appear near 15° from celestial north, thus it would not be as large 15 degrees from celestial north, thus it would not be as large negative peak in the diagonal component distortion at T/2. By analyzing a supposed 10 km high ellipsoidal distortion on the sun with a tilted axis near 45°, Dicke was able to explain nearly all of the fluctuations in the oblateness signal in terms of the viewing of his instrument. The solar ellipsoid rotated with a period near 12.22 days about the mean axis of the sun's surface rotation. Other periods would give rise to different fluctuations when coupled with the changing viewing platform of the earth.

In particular, Dicke(1976) performed an analysis around P=0, when only odd harmonics in the diagonal component should appear (due to the appearance of a negative signal from the opposing limb), and only odd harmonics <u>did</u> appear for a core period of 12.22 days, but when the period was doubled only the second harmonic appeared. This adds support for his interpretation.

We have looked to see if there is any evidence in a power spectrum of the sunspot record for a feature near this period.

II. Spectrum Analysis

We have analyzed the run of Zurich daily sunspot numbers (see Waldmeier 1961) extending from January 7, 1849 to November 28, 1970 by a least-squares procedure. We minimize

$$V_3 = \sum_{n=1}^{N} \left[X_n - a - b\cos\left(\frac{2\pi}{P}n\right) - c\sin\left(\frac{2\pi}{P}n\right)\right]^2 \qquad (2.1)$$

where X_n is the sunspot number and n counts days from 1 to 44520, varying a, b and c for a range of values of the period P. Then $S = b^2+c^2$ provides an estimate of the spectral power at period P. The sums required to calculate the least-square fits were generated using a 131072 element FFT. Figure 1 displays the estimated spectral power as a function of period for periods greater than 4 days. The large number of spectral estimates (32768) precludes plotting all the individual points so the spectrum has been grouped into 64 frequency intervals each containing 512 spectral estimates. The median, 70th, 90th and 99th percentiles for each of the 64 bins are displayed in Figure 1. The sun symbol in Figure 1 shows the peak at 12.0715 days. There is obviously a great deal of power in the very low frequency portion (associated with the eleven year solar cycle) and in the range of the familiar surface rotation periods.

It is appropriate to ask the question of significance because there is always one largest peak, even when one analyzes random data. Many authors have found a number of significant peaks in the sunspot spectrum (see Wolff, 1976; Xanthakis, 1967 for further discussion), however, nearly all have only analyzed the spectrum using monthly averaged sunspot number to discover longer periodicities. Ward and Shapiro (1962) performed a reasonably complete picture of the spectrum, but their analysis with daily data only covered the years 1920 - 1924 and thus their spectral resolution precluded the finding of a high but narrow peak of the type uncovered in the present analysis. Nevertheless, their Figure 4 does reveal a slight peak near 12 days. One common method used to assess the significance of a least-squares fit is the F test (see for example Rao 1973). We form the statistic

$$F_{2,N-3} = \frac{N-3}{2} \frac{V_1 - V_3}{V_3} \tag{2.2}$$

where V_3 is defined by (2.1) and V_1 is the sum of the squared deviations from the mean. We expect this statistic to be distributed approximately as $F_{2,44517}$ if the following assumptions are reasonably well satisfied: the residuals, used to form the sums V_1 and V_3, (a) are distributed normally with mean zero and the same variance, and (b) are uncorrelated day to day.

However, one can see that the sunspot numbers are highly correlated from day to day by simple inspection of the data (see Waldmeier 1961). Furthermore, the daily sunspot numbers are very "skewed" compared to a sample selected from a normal population with the same mean. It is true that the F test is "robust" (i.e. it is fairly insensitive to the assumptions of normality being exactly satisfied) but the sunspot number data are far from normally distributed and we therefore cannot expect the F statistic constructed using the least-square fits to the raw sunspot data to be distributed as $F_{2,44517}$.

We can see that the F statistic constructed from the least-square spectral estimates is not distributed as $F_{2,44517}$ from the F statistics for the high-frequency (short-period) portion of the least-square spectrum. For the 24538 highest-frequency least-square estimates (periods from 4 to about 16 days), none exceeds the 1% significance level. We have in fact oversampled in frequency by a factor of about 3 to assure that no strong features are neglected, so that there are only about 8000 independent spectral estimates in this range of periods. The probability that none of 8000 independent F statistics would exceed the 1% level is $(.99)^{8000} \approx 10^{-34.9}$. Clearly, the usual F test does not provide an adequate estimate of the significance of a particular spectral feature.

Whether or not the original data are normally distributed, the least-square estimates of b and c of equation (2.1) are effectively sums of a large number of products of individual data and sines or cosines for which the expectation values are zero, so that they may be expected to be distributed normally with mean zero if there are no periodic "signals" in the data at the frequency in question. We therefore expect the spectral estimates to be distributed as $\sigma^2\chi^2$ with two degrees of freedom ($\sigma^2\chi^2_2$), where σ^2 is the variance (assumed equal) of b and c. The expected value of the $\sigma^2\chi^2_2$ statistic is $2\sigma^2$. There is no simple way to estimate what value to expect for σ; indeed, inspection of Figure 1 indicates it depends strongly on frequency.

We are primarily interested in periods near Dicke's suggested (synodic) rotation period of 12.64 days. We expect that the large broad peak near 27 days is real and due to the combination of a non-uniform distribution of sunspots on the surface of the sun and the differential rotation of the surface. We therefore will restrict our attention to the 24538 highest frequencies (periods from 4 to about 16 days). The obvious trend in this portion of the spectrum was removed by fitting a quadratic in log(f) to the log of the estimated spectral power averaged over 10 bins approximately equally spaced in log(f). Having placed the high frequency spectral estimates on approximately the same footing, we are in a position to estimate <u>empirically</u> the variance needed to specify the probability density.

The cumulative density function for a statistic (in this case the adjusted spectral estimates, S) distributed as $\sigma^2\chi^2_2$ is

$$C \equiv P(S'<S) = \frac{1}{2\sigma^2}\int_0^S e^{-S'/2\sigma^2}\,dS' = \left(1 - e^{-S/2\sigma^2}\right) \qquad (2.3)$$

We can estimate σ^2 by comparing the theoretical cumulative distribution with an empirical cumulative distribution constructed from the adjusted spectral estimates. The spectral estimates are sorted and each of the estimates is assigned a value of C according to

$$C_i = (i-.5)/24538 \qquad (2.4)$$

where i=1 for the smallest adjusted spectral estimate and i=24538 for the largest.

We have used three different methods to estimate σ^2 from the sorted adjusted spectral estimates. First we fit the empirical cumulative distribution by varying $1/2\sigma^2$ to minimize

$$\sum_{i=1}^{24538} \left[\frac{1}{2\sigma^2} S_i + \ln(1-C_i)\right]^2 \qquad (2.5)$$

and obtain $\sigma^2 = .5025$. Since we expect $-\frac{1}{2} S_i/\ln(1-C_i)$ to be approximatel equal to σ^2, we can average this quantity and the reciprocal of it to obtain the second and third estimates, which are $\sigma^2 = .4981$ and $\sigma^2 = .4996$ respectively. Combining these estimates for σ^2 with the adjusted power at 12.0715 days ($S=13.46$), we estimate (a posteriori) the probability that this large a peak would occur by chance to be 1.53×10^{-6}, 1.35×10^{-6} or 1.41×10^{-6} respectively.

As we have indicated, we expect $C \simeq (1-e^{-S/2\sigma^2})$. A plot of $\ln(1-C)$ versus the sorted adjusted spectral estimates therefore should be nearly a straight line. In Figure 2 the theoretical relation between $(1-C)$ and S for $\sigma^2 = .5$ is the broken line and the actual adjusted spectral estimates are indicated by the solid curve. The points corresponding to the five largest adjusted spectral estimates are indicated by the numbers 1 through 5. As expected, the empirical and theoretical curves are quite close except for the two largest adjusted spectral estimates which are associated with the peak at 12.0715 days. The deviation of the empirical curve from the theoretical line for $(1-C)$ between $\sim 10^{-2}$ and $\sim 10^{-4}$ is primarily due to an excess of large adjusted spectral estimates associated with harmonics of the broad peak near 27 days period.

We conclude from the above analysis that the adjusted spectral estimates may reasonably be assumed to be distributed as $\sigma^2\chi_2^2$ with $\sigma \simeq .5$

and that the (*a posteriori*) probability that the peak at 12.0715 is due to chance is $\sim 1.4 \times 10^{-6}$. However, we must take account of the fact that the period 12.0715 was not chosen *a priori*, but inferred from the data.

Dicke (1976) interpreted the results of his analysis as evidence for some solar rotation with a period of 12.64±.12 days (synodic). Dicke's quoted error estimates for the period are calculated from a maximum likelihood treatment of the residuals in the Princeton oblateness data after an estimate of static oblateness is removed (Dicke 1976). We prefer to adopt a somewhat more conservative error estimate. The time interval analyzed with the Princeton oblateness data is 97 days (Dicke 1974, 1976); we will take the uncertainty in any frequency estimate to be $\pm 1/2T$ (Bendat and Piersol 1971). This gives an expected error in frequency of $\pm 5.15 \times 10^{-3}$ d^{-1} or a range in period of 11.87 to 13.52 days.

We may now estimate the probability that a peak with the significance of the 12.0715 day peak would occur by chance in the interval 11.87-13.52 days. This range in period contains 1,352 spectral estimates so that we estimate the probability of the 12.0715 day peak occurring within this range by chance as $(1.352 \times 10^3) \times (1.4 \times 10^{-6})$ or $\sim 2 \times 10^{-3}$. As we have already indicated, only ~1/3 of the spectral estimates are independent, so that calculating the probability estimate as though all 1352 spectral estimates were independent produces a conservative probability estimate.

The adjusted spectral estimates in the range 11.87–13.52 days are displayed in Figure 3 with confidence levels corresponding to the probability that none of the 1352 adjusted spectral estimates would exceed the indicated values.

As a check on the foregoing analysis, we differenced the sunspot data and analyzed the differenced data in the same manner as the undifferenced data. The analysis of the adjusted spectral estimates produced similar results in all three methods of estimating σ^2 and the probability estimates. Since the differenced data appears nearly uncorrelated day to day and most of the power at low frequencies is removed, we performed an F test on the least-square fit to the differenced data at 12.0715 days, and obtained a (chance) probabilty estimate of 6×10^{-7} (about a factor of 2 lower than that from the analysis of the cumulative distribution of the adjusted spectral estimates).

We have also split the data into halves and separately analyzed the first and second half of both the raw and differenced data. The analysis of the adjusted spectral estimates gives nearly the same results for all three methods of estimating σ^2 for both raw and differenced data for the entire data run and each half considered separately. The products of the (chance) probability estimates for the peak at 12.0715 days for each half considered separately are approximately equal to, but slightly smaller than, the probability estimates for the entire data run for both raw and differenced data.

Shapiro (private communication, 1979) has examined the sunspot record from 1884 to 1970 using the Blackman-Tukey approach to search for this peak. A peak near our period was found when

5000, 10000, and 20000 power spectral estimates were examined. The peak, although apparent, was within the range of the sampling fluctuations judging from the appearance of larger peaks at other frequencies. The Blackman-Tukey approach allows a measure of significance to be ascertained; the peak was not quite significant at the 5 % level. This could be due to one or more of the following: (1) the differing sunspot data employed, (2) the differing number and periods of the spectral estimates used to resolve our supposed high narrow peak, or (3) the differing methods between FFT and Blackman-Tukey approaches.

In addition to the highly statistically significant 12 day peak in the power spectral curve itself, this period becomes apparent in the sunspot record by the appearance of beats with several peaks near 27 days as well as resonances with the 11 year and the 22 year solar activity cycle.

Table 1 shows periods in the raw sunspot power spectrum that relate to the 12.0715 day period. The power is the square of the amplitude. Beats with the three 27 day peaks shown result when a difference in the angular velocities of the 12 and 27 day rotations is assumed, suggestive of an internal rotation period being responsible for the 12 d peak. Harmonics of the 11 year and 22 year peak occur near 12 days at both plus and minus these frequencies due to these signals representing a modulation of the 12 d period. Several harmonics and subharmonics are shown. None appear of great significance. The appearance of subharmonics is explicable by assuming the 12 d peak results from an increase in sunspot number (by about 4) due to the added presence of one detectable spot a fraction of the time each 12 day rotation. The significance of any peak may be estimated by comparison with Figure 1, taking the amplitude squared. None of these peaks, by itself, is of any great significance, nevertheless, it is a useful check to see their presence in the spectrum. In addition, the 12.0715 day peak shows up as significant, in both halves, when the data is subdivided in two.

III. Discussion

The peak at 12.0715 days, with approximately equal adjusted spectral estimates in the first and second halves of the data, is suggestive of the influence of a stable, long-lived periodic process, such as the rotation of the sun's core. However, the data could be reconciled with a synodic rotation period of the core which is a multiple of the 12-day period. In particular a core rotating with a 24 day synodic period could cause an apparent 12-day periodicity if the disturbance produced by the core has not only a possible $m = 1$ component but also an $m = 2$ component, where m is the azimuthal mode number. On the other hand, to attribute a period of 36 days or more to the core seems unreasonable, since the convective zone would then be subject to decelerating torques from both the core and the solar wind.

We have also split the data into even and odd activity cycles, and find that the adjusted spectral power estimate at 12.0715 days is ~7 times as large for odd cycles as for even cycles. This suggests that, if the peak at 12.0715 days is due to core rotation, the coupling with surface phenomena is probably magnetic. Unless the relic magnetic field is confined to one compact "active region", the coupling between the core and convective zone must then have a strong $m = 2$ component.* Fol-

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*Indeed the presence of a peak in the spectrum at about 13.5 days indicates that even the convective zone has some kind of $m = 2$ structure.

lowing this line of argument. the sunspot data alone seem to favor the interpretation of the 12-day peak as being produced by a core rotating with a synodic period of 24.14 days coupling magnetically to the convective zone. We realize, however, that if Dicke's (1976) interpretation of the Princeton oblateness data is correct, the 12-day periodicity of the sunspot data is to be interpreted in terms of a 12-day core rotation.

Among the persuasive arguments which Dicke (1976) advances in favor of his interpretation, we are particularly impressed with the following: Only odd harmonics of the rotation period should appear in the diagonal component of the Princeton "oblateness" data when the projections on the plane on the plane of the sky of the rotation axes of the sun and of the earth are aligned. For an interval of time satisfying this condition, Dicke finds that his data yield only odd harmonics for an assumed rotation period of 12.22 days (sidereal) but not for assumed periods near 24 days.

Superficially, our findings seem to disagree with Dicke's: Dicke (1976) proposes that there are two distortions per rotation, which one might expect to correspond to a peak in the sunspot spectrum at about 6 days rather than 12 days. However, Dicke's data are obtained by summing signals from diametrically opposed pairs of windows: hence what may in reality be a single localized distortion would in any event appear, from the Princeton data, as a diametrically opposed pair of distortions.

Dicke (1978) has kindly informed us that when the 12.0715 day period is used as a constraint to fit the Princeton data, the regression coefficients yield a fit with a significance of approximately 3σ. We feel this indicates that, for the purpose of assessing the significance of the 12.0715 day peak, our use of $\pm 1/2T$ as an estimate of the frequency uncertainty is not unreasonable.

To summarize, we find a prominent peak in the sunspot power spectrum with a period of 12.0715 days which is consistent with Dicke's (1976) 12.64 day period if the uncertainty in the period inferred from the Princeton data is $\sim\pm 0.8$ days. The probability that a peak of this spectral power would occur within these limits by chance is estimated to be $\approx 2 \times 10^{-3}$. The possible real difference between Dicke's period and our period suggests a phase drift over short periods of time. Varying phase is a common feature of solar activity, with solar cycles behaving in a periodic manner, but with "short" and "long" cycles present. This may hinder certain analyses from locating this periodicity.

One of us (KHS) has benefitted from discussions on this topic with R.H. Dicke and R. Shapiro. This work was supported in part by the National Aeronautics and Space Administration under grant NGL 050-020-272 and Air Force Grant F19628-77-R-0310.

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TABLE 1

Period (days)	Amplitude	Resonance with 12.0715 days	Comparison Peak	Comparison Peak Amplitude
12.0715	0.977			
26.9529	1.86	21.8639	21.8818	1.05
27.0530	2.29	21.7982	21.7583	1.09
27.2442	1.57	21.6756	21.6720	1.14
11 years	4.1	12.1079	12.1033	0.41
11 years	4.1	12.0353	12.0349	0.30
22 years	7.2	12.0897	12.0904	0.64
22 years	7.2	12.0534	12.0548	0.43

Harmonics and Subharmonics

With 12.0715 Days	Amplitude	Actual Location
6.0357	0.168	6.0349
4.0238	0.173	4.0236
24.143	0.871	24.143
36.215	0.391	36.208
48.286	0.768	48.313

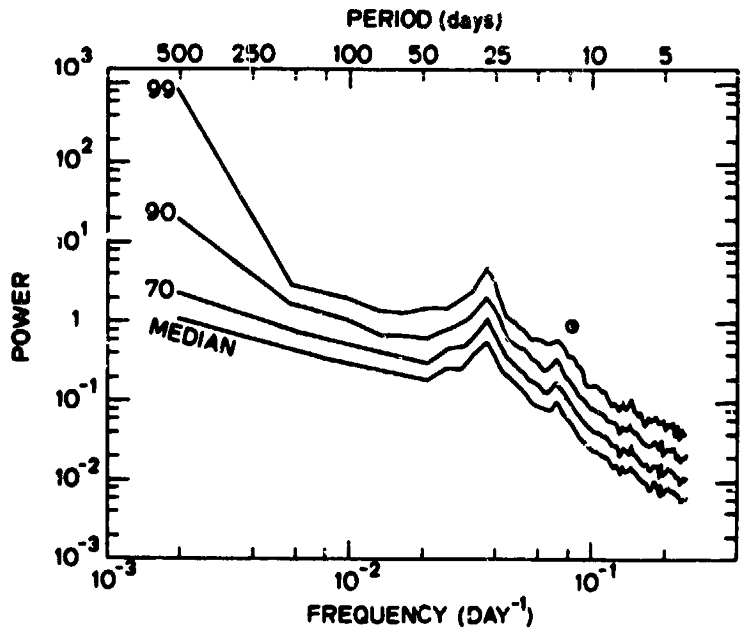

Figure 1. Least-squares power spectrum generated as explained in the text. The median, 70th, 90th and 99th percentile estimated spectral powers are plotted for each of 64 equally spaced frequency bins. The sun symbol corresponds to the peak at 12.0715 days.

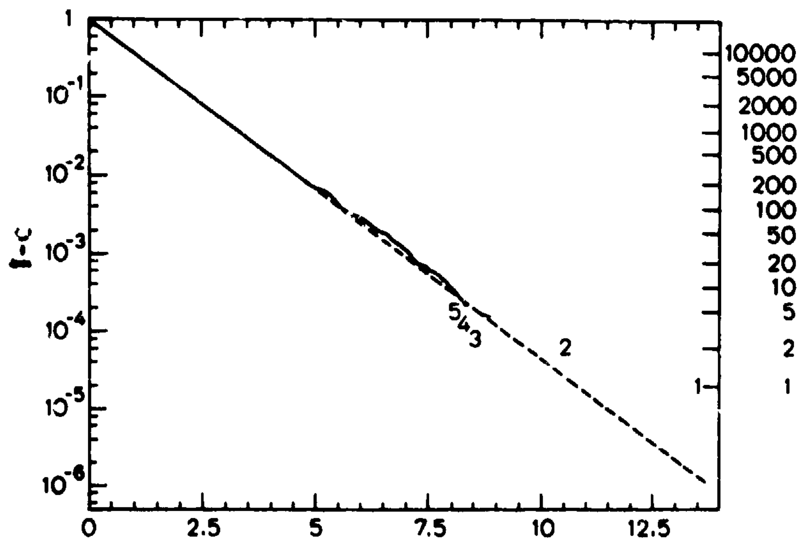

Figure 2. The quantity (1-C), the probability that a spectral estimate will exceed S, as a function of adjusted power, S. The solid curve corresponds to the empirically determined cumulative distribution, the broken line to the cumulative distribution for a variate distributed as $.5\chi^2$ with two degrees of freedom. The right vertical axis is labeled by the rank of the corresponding adjusted spectral estimate. The numbers 1 through 5 indicate the five largest adjusted spectral estimates.

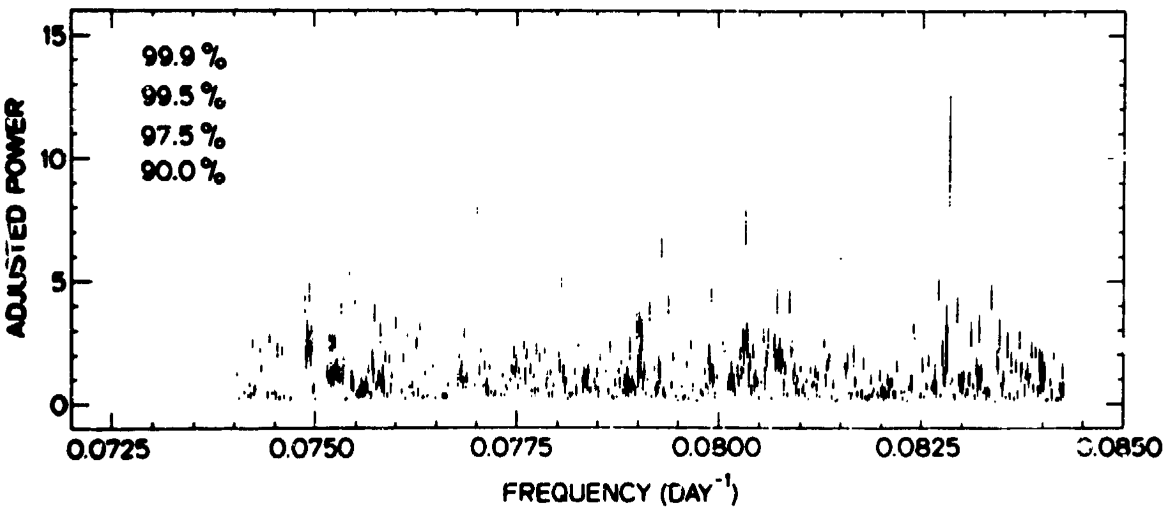

Figure 3. Adjusted spectral power versus frequency for the frequency interval $7.911 \times 10^{-2} \pm 5.15 \times 10^{-3}$ day^{-1}. This frequency interval corresponds to a range in period of 11.87 - 13.52 days and contains 1352 adjusted spectral estimates. The confidence levels correspond to the probability that none of 1352 spectral estimates distributed as $.5\chi^2$ with two degrees of freedom would exceed the indicated spectral power.

PROBLEMS OF LARGE SCALE SOLAR MAGNETIC FIELDS, THE CORONA, AND THE HELIOSPHERE AS RELATED TO THE SOLAR CYCLE AND THE ROLE OF SCADM

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(No paper submitted)

QUESTIONS AND COMMENTS

COMMENT BY: D. L. Glackin, JPL

DIRECTED TO: A. Hundhausen

I would like to stress the desirability of flying SCADM at the same time as polar passage of the Solar Polar spacecraft. A white light coronagraph should be flown, to complement Bob MacQueen's coronagraph on the NASA Solar Polar spacecraft. This would allow the three-dimensional reconstruction of the corona and a determination of the rate of divergence of field lines in polar holes, which is related to the acceleration of the solar wind.

COMMENT BY: J. V. Lincoln, Director, WDC-A for Solar Terrestrial Physics

DIRECTED TO: A. Hundhausen

You mentioned the use of Hα solar maps for long-term synoptic studies. I would like to point out that Report UAG-70 by Pat McIntosh presents such Hα maps for solar cycle 20. These maps can be used for study with other phenomena such as the K-corona synoptic maps. The Report can be obtained from the World Data Center-A for Solar Terrestrial Physics.

COMMENT BY: K. Schatten, Astronomy Department, Boston University

DIRECTED TO: A. Hundhausen

I wonder why you stress only solar wind streams, and whether their field polarity is positive or negative, if you are trying to understand problems such as cosmic ray modulation. The IMF (with all its structure - kinks, loops, filaments, etc.) interacts with cosmic rays directly, not high speed streams. So I think in examining such problems the real IMF (as observed by interplanetary spacecraft) should be studied and not just sector patterns.

COMMENT BY: A. Skumanich, HAO

DIRECTED TO: A. Hundhausen

The question of the long-time evolution and presence of a solar wind and dynamo can also be addressed on a much longer time scale than that given by C^{14} records. I refer to the stellar parameter of age. Comparisons of normal main sequence G stars of different stellar ages with the sun show a systematic chromospheric and rotational decay with age. As has been discussed in the literature, this suggests a well defined but secularly changing average wind and dynamo for normal G-dwarfs.

ON

STEREOSCOPIC VIEWS OF THE X-RAY CORONA

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Abstract

The Solar Cycle and Dynamics Mission (SCADM) presents a unique opportunity to increase our understanding of physical processes in the extended solar atmosphere, particularly with regard to the large-scale, three-dimensional structure of the solar corona, the influence of coronal structure on the formation of the solar wind, and the relationship of coronal structure to underlying solar phenomena. The uniqueness of this opportunity is provided by the simultaneous availability of coronal observations at high solar latitudes from the Solar Polar Mission (SPM). The combination of coronal observations from SCADM and SPM enhances the value of the data in many ways relative to that which could be obtained by either spacecraft alone.

The mathematical developments discussed in this paper were presented at the Optical Society of America's Topical Meeting on Image Processing for 2-D and 3-D Reconstruction from Projections: Theory and Practice in Medicine and the Physical Sciences, August 4-7, 1975, at Stanford, CA.

N80-17958

SPATIAL EVOLUTION OF MAGNETIC FIELDS AS SEEN IN CORONAL STREAMERS TO 12 $R_\odot$ DURING THE SOLAR CYCLE

By

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ABSTRACT

Outer coronal photographs have been made from high altitude aircraft at the solar eclipses of 1966, '70, '72, '73, and '79. These sample various times in the solar cycle. Image processing techniques allow us to display on a single photo coronal streamers extending from the solar limb to 12 $R_\odot$ (and possibly to 20 $R_\odot$ for the 1979 eclipse). Thus for the first time one can study the evolution of streamers as they distort magnetic field lines to large distances from the sun. We will show that this distortion is varied and often unexpected. Polar plumes can be traced beyond 8 $R_\odot$ diverging apparently along dipole field lines. This divergence varies along the solar cycle. Nonpolar streamers show various changes, the most common of which is their tendency to become radial beyond 3-5 $R_\odot$ as if controlled by the solar wind. We propose that such photographs can be used to guide theoretical studies of streamer evolution far from the sun.

I. INTRODUCTION

The Field Testing (J) Division of the Los Alamos Scientific Laboratory has flown an instrumented NC-135 jet aircraft to observe six total solar eclipses. One of the experiments on these missions was photographic polarimetry of the corona to 12 $R_\odot$. The method used is similar to that used by coronographs on the ATM and SMM satellites. This experiment has been very successful and we have a wealth of well calibrated data from 5 of the 6 eclipses (poor data from the first attempt in 1965). Figure 1 shows the dates of these eclipses plotted on a graph of sunspot number versus time for cycles 20 and 21.

Although the photographs (approximately 30 per eclipse) were not made to be picture quality, we have been able through computer, image enhancement techniques to produce remarkable portraits of the corona from 1.2 to 12 $R_\odot$ for 4 of the 5 eclipses. The 5th (1966) will be done shortly.

II. THE DATA

Figures 2-5 are prints of the computer generated negatives for these four eclipses as indicated. Note the following points:

- All photos from same specially-designed Los Alamos camera--f/6, f = 600 mm--with 70 mm roll film.
- These negatives are then image-processed by computer.[1]
- Heliocentric north is given approximately on the figures.
- Excepting for the 1973 picture--these figures represent a first attempt at processing and can be improved.
- The 1970 picture was made from a partial set (12 of 36) of exposures and is of lesser quality.

III. DISCUSSION

We feel these are important contributions to the study of the corona-solar wind interface (we take this to be in the region approximately 2-12 $R_\odot$) since they apparently map the spatial evolution of magnetic field lines as the electron corona expands outward.

The study of these pictures has just begun and so no detailed conclusions can be drawn from them yet. However several broad observations and generalizations can be made and several more can be put forward as requiring more such data to confirm them.

1) These photographs are detailed enough to allow close comparison with ATM photos and with ground based photos through radially graded filters.

2) There are unexpected changes in streamers as they evolve spatially from 3 $R_\odot$ to beyond 6 $R_\odot$.

3) There are definite differences in the number, nature and distribution of streamers as a function of solar cycle activity.

4) Polar plumes photographed with ground based high resolution cameras can be traced as streamers out to 8 $R_\odot$ and beyond. These streamers seem to serve as indicators of the solar dipole magnetic field. Comparison of this set of 4 eclipses, 2 near maximum and 2 on the declining side of cycle 20, shows that the dipole field apparently varies with solar activity. Inspection of the 1966 (rising side of cycle 20) unprocessed negatives shows that the polar divergence is similar to those of 1972 and 1973. Thus polar streamers near solar maximum are strong and bend in an apparent dipole field, but do not diverge rapidly, while those on both rising and declining branches of activity are weak and diverge rapidly.

These observations seem to support the general model of coronal variation with solar cycle described by Hundhausen.[2]

5) Nonpolar streamers appear capable of being grouped into a small number of kinds, however, their spatial evolution appears also to be a function of their local environments, i.e., neighboring streamers seem to interact. Also, while many streamers appear similar, there are striking examples of unique ones most notably the double y streamer seen in the southwest quadrant on the 1973 picture.

6) Many streamers seem to diverge at large distances from the sun. The 3-dimensional nature of the divergence needs to be investigated.

7) Nonpolar, non-radial streamers become more and more radial at large distances from the sun. This is most striking on the west limb of the 1979 eclipse. This effect, as well as the straightening of polar streamers, seems to be an indication of solar wind influences.

This discussion has omitted transients which were present above the west limb in 1973 (4-10$R_\odot$) and 1979 (1 to 4 $R_\odot$). It also omits discussion of streamers beyond 12 $R_\odot$. In 1979 the camera was offset in an attempt to record the equatorial region to 20 $R_\odot$. These pictures have not yet been processed, nor have most from 1970 and all from 1966. Thus we are discussing an incomplete set. Still, these observations seem enough and convince us that an effort to record the corona beyond 6 $R_\odot$ at regular intervals during a solar cycle combined with computer image enhancement could greatly increase our understanding of the interaction of large scale magnetic fields and the solar wind.

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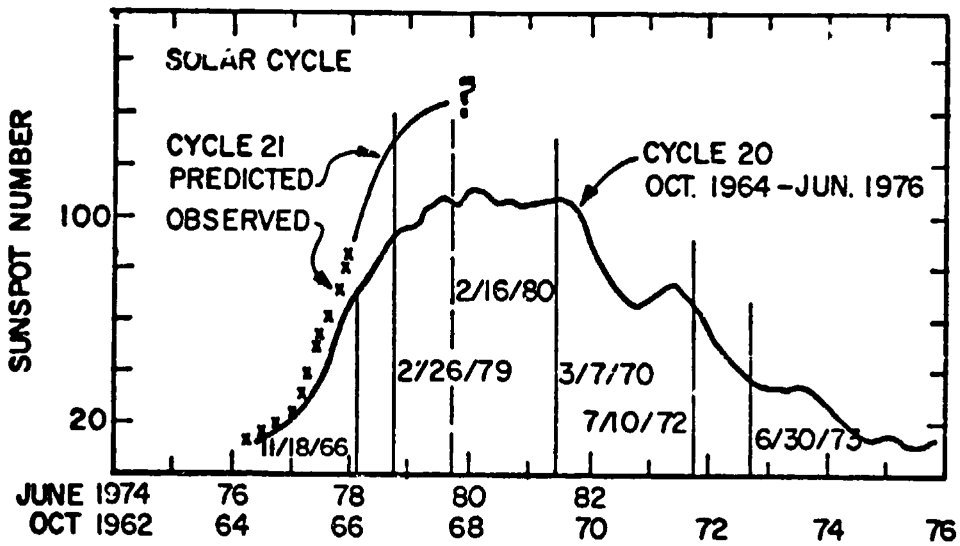
SOLAR CYCLE
CYCLE 21 PREDICTED
OBSERVED
?
CYCLE 20
OCT. 1964 - JUN. 1976
SUNSPOT NUMBER
100
20
11/18/66
2/26/79
2/16/80
3/7/70
7/10/72
6/30/73
JUNE 1974
76
78
80
82
OCT 1962
64
66
68
70
72
74
76

Figure 1

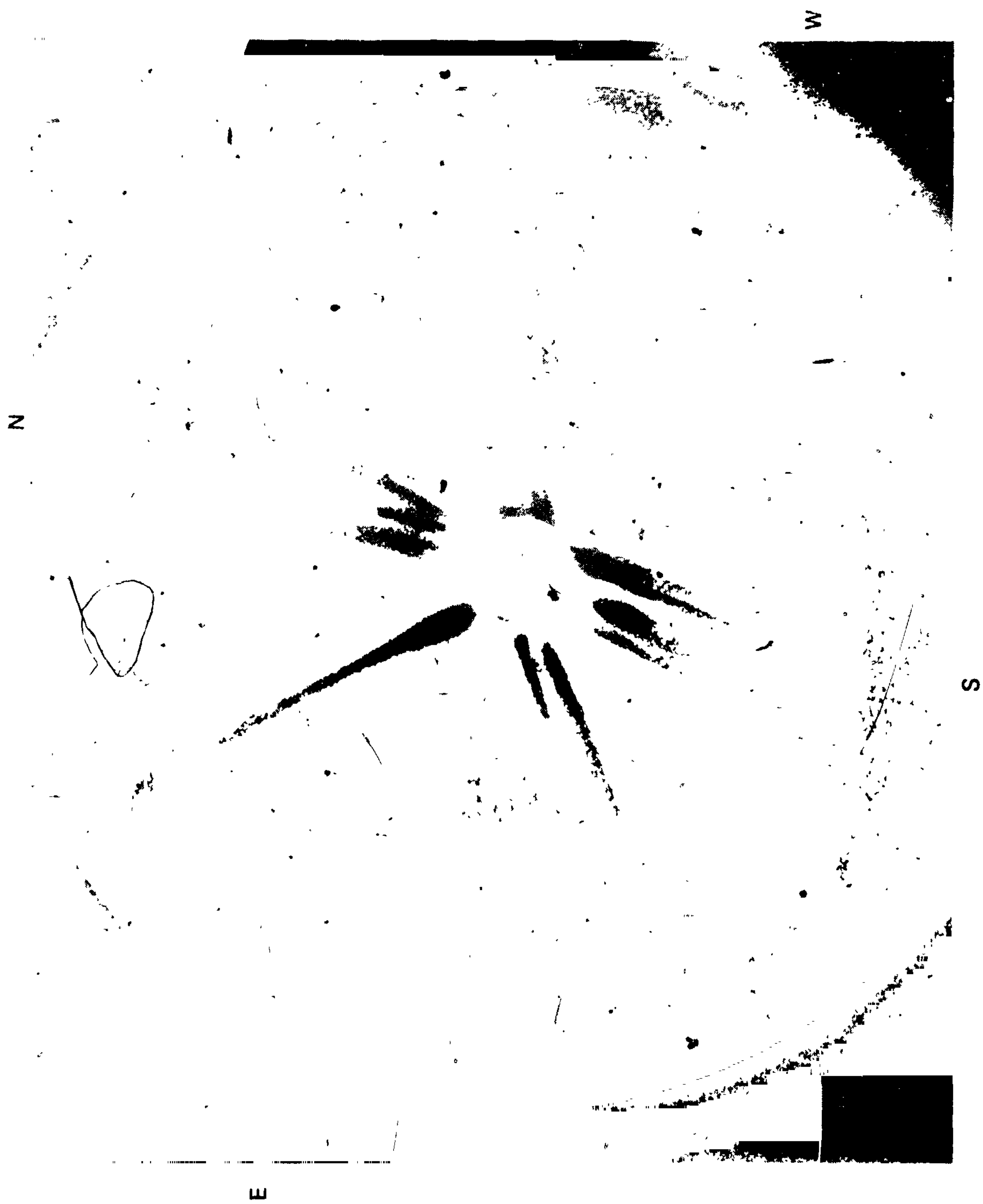

Figure 2 -- March 7, 1970

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

Figure 3 -- July 10, 1972

Figure 4 -- June 30, 1973

Figure 5 -- Feb. 26, 1979

N80-17959

THE DEPENDENCE OF CORONAL HOLE SIZE ON LARGE SCALE MAGNETIC FIELD STRENGTH

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INTRODUCTION

A comprehensive model of coronal structure is a necessary requirement for studies of coronal energetics, of global flows of the solar wind, and for reliable solar-terrestrial predictions. An ideal model might depend on the fewest possible observable parameters, but include all possible empirical relations of how the physical processes in the corona depend on the observables. The simplest conceivable model of this type would use only measurements of the photospheric magnetic field for the boundary condition because it is this field which apparently permits and modulates extended energy deposition in the corona (Suess, 1979). There is little evidence for significant variations in temperature and density at the chromosphere either between coronal holes or over a solar cycle, so these boundary conditions might initially be taken as invariant. However, any such model is presently nothing more than an academic exercise, and will remain so until a mission like SCADM presents the theoretician with an empirical description of chromospheric UV/EUV emission—with resulting derivable mass and energy fluxes between the photosphere and the corona, together with coronal structure, and the temperature and density throughout the corona as observed and related to the photospheric magnetic field over an entire solar cycle.

We will describe here one coronal model which is a logical extension of earlier models to allow a closer relationship to the photospheric magnetic field as it is observed daily, and then briefly outline how our calculation can be further improved in anticipation of our just-stated requirement for eventual interpretation in terms of empirical coronal-photospheric relationships over a solar cycle.

PREVIOUS CORONAL MODELS

To model coronal structure from the photosphere to a few solar radii is necessarily a global problem because there will be both magnetically closed and open regions involving magnetostatic and magnetodynamic equilibria, and there will be some sort of a neutral surface dividing the closed and open regions. One example of such an MHD model is that of Pneuman and Kopp (1971). They calculated fieldline geometry for one specific case, with the results shown in Figure 1. Their approach to coronal MHD flow was to:

1. Assume isothermal flow with a constant temperature and density on the surface of the sun.
2. Assume a known geometry for the cusp.
3. Begin with a specified current distribution and iterate on that distribution until a pressure equilibrium was attained.
4. Assume axisymmetry, no rotation, no momentum addition, and north-south symmetry.
5. Limit the analysis to between 1 and 5 solar radii.

They also treated only the case of a purely vector dipole at the surface of the sun, and examined only one field strength. It is important to note that this calculation was dependent on knowledge of the nature of the cusp and, although pioneering, was extremely limited in its ability to explore parameter space.

In a different calculation Endler (1971) used the same boundary conditions and assumptions, other than that about the cusp, in an initial value/time relaxation calculation. He found the same end state as Pneuman and Kopp, proving the accuracy of their assumption. Endler's approach is inherently more powerful because it does not require prior knowledge of the character of the cusp and could easily be used to relax geometrical symmetry assumptions.

We note that Endler used an explicit time differencing scheme which would have to be modified to be partially or totally implicit in order to include the effects of thermal diffusion, although an explicit scheme can be used to examine the effects of momentum addition and, for astrophysical problems, rotation. Endler's work has recently been reproduced and his results verified by Weber (1978).

The flexibility of the time relaxation approach allows analyses like those of Endler and Weber, with some modification, to be used to study the variation of coronal hole size under varying boundary conditions. In particular, the variation of the polar coronal hole over portions of the solar cycle can be studied under the assumption of axisymmetry. This we have done in a model described in the next section.

THE PRESENT CORONAL MODEL

The MHD global coronal model we have used to study the evolution of coronal structure is, in many ways, similar to Endler's (1971). We have developed a numerical solution to the MHD equations of motion under several simplifying assumptions in the distance range of 1 to 5 solar radii. Our assumptions are:

1. Axisymmetric flow with no rotation, resulting in two-dimensional flow in a meridional plane.
2. Zero viscosity and infinite electrical conductivity.
3. Polytropic, single fluid flow.
4. No momentum addition.

With these assumptions, the azimuthal velocity and magnetic field are zero, and the dependent variables are the radial and meridional velocity and magnetic field, the pressure and the number density—all functions only of radius and polar angle. This reduces the full set of MHD equations to a set of six equations, and these are shown and discussed by Steinolfson et al. (1978).

Except for the generalization from isothermal flow to polytropic flow, these assumptions are identical to Endler's. Nevertheless, we would like to remark on two points. First, Suess et al. (1972) employed a polytropic fluid to simulate a specific polar coronal hole. Because they were able to closely reproduce the observed density throughout the entire coronal hole, the results of the analysis became equivalent to substituting the observed density distribution for the polytrope assumption. They found that a polytropic index, γ, of 1.05 gave this convenient result. The implication is that for the coronal hole studied, the chosen polytropic index and no momentum addition gave a satisfactory description of the actual extended energy deposition. The implication for the work described here is that a polytropic index of 1.05 might give a reasonable, although crude approximation to actual extended energy deposition in the limited range of 1 to 5 solar radii. The second point concerns the assumption of infinite electrical conductivity. This proves to be no limitation under the initial conditions described below in the examples we treat. However, if we were to attempt to simulate relaxation from an open to a closed coronal field configuration, the assumption of infinite electrical conductivity would have to be altered.

The numerical approach we have used to solving our set of six equations is also described by Steinolfson et al. (1978). We treat the problem by taking an initial configuration and allowing it to relax, in time, to a steady, stable configuration of closed and open field regions. In using this approach, the cusp geometry is automatically determined. Furthermore, if we were to generalize to more complex geometries, the calculation could locate the cusp anywhere in the computational grid. The equations are reduced to a finite difference form using a modified Lax-Wendroff differencing grid employing explicit time differencing. Because high spatial resolution is required close to, but not far from the sun, we also convert the radius coordinate, r, to $\lambda = 1/r$. The grid intervals, $\Delta\lambda$ and $\Delta\theta$ are held fixed at $0.01 R_{\odot}^{-1}$ and 0.01 radians respectively so that the grid spacing in radius becomes larger further from the sun The time step, Δt, is limited such that

$$\Delta t \leq \frac{1}{\Delta\lambda C}$$

$$C = \sqrt{C_s^2 + C_A^2}$$

and C_s and C_A = the sound and Alfven speeds respectively in order to insure numerical stability.

Using this numerical approach, coronal geometries were computed for two photospheric field strenghts. As boundary conditions, both cases used a temperature and density on the surface of the sun of

$$T_o = 1.8 \times 10^6 \text{ °K}$$

$$N_o = 2.248 \times 10^8 \text{ cm}^{-3}$$

and a polytropic index of 1.05. The field geometry at the surface of the sun was specified to be a vector dipole, but with different field strengths. The initial state was, simply, a spherically symmetric solar wind derived from the above-stated boundary conditions on density and temperature, upon which was superimposed, at time zero, a dipole potential field of the prescribed strength at the surface of the sun. This dipole configuration is illustrated in the top panel of Figure 2. These initial states were then allowed to relax to an apparent, stable state. The final states are illustrated in the middle and bottom panels of Figure 2 after a dynamical time of 16 hours, and a computational time involving several hundred numerical time steps.

The two cases in Figure 2 are for a plasma beta of 1 (middle panel) and 4 (bottom panel) at the equator and surface, corresponding to a surface field strength of 1.66 gauss and 0.83 gauss respectively. Under the decreased field strength, the last closed field line maps to a latitude of about 27 1/2° as compared to a latitude of 38° in the middle panel. This corresponds to an increase in area of the coronal hole of between 35% and 40% when the field strength is reduced by a factor of two.

These two sample calculations cannot be used to derive much in the way of quantitative results, but already a qualitative conclusion can be made. This is that the change in polar coronal hole size during the solar cycle cannot simply be due to changes in field strength because changes of the required magnitude to reproduce the observed change in hole size are simply not allowed by the available data—a conclusion that admittedly has been anticipated using other reasoning.

Several problems remain to be solved using this particular calculation, including the question of whether the configuration is completely stable. It is apparent in the bottom panel of Figure 2 that the fieldlines between 2.5 and 5 solar radii and near the equator are not radial—as they should very nearly be after a dynamical time of 16 hours. This may reflect a real hydrodynamic instability, and has an apparent counterpart in coronal observations (G. Newkirk, private comm.). This problem, evolutionary rates under varying conditions, and geometrical dependence on deviations from a simple dipole boundary condition are just a few of the problems we can address. However, the viability of any physical deductions would depend on a comprehensive set of observations over widely varying solar conditions.

IMPROVED CORONAL MODELS

Obviously the above model is limited by the polytrope assumption. This limitation can be removed by conversion to an implicit differencing scheme and inclusion of the effects of thermal diffusion. It is possible that a computational advantage would also result from this conversion, even though implicit differencing schemes are usually slower and require more memory, because severe limitations on the allowable time step are imposed by increasing field strengths. In an implicit shceme, the size of the time step is limited only by truncation error, whereas explicit schemes are limited by the criteria in Equation (1) in order to maintain numerical stability. For these reasons, we are presently favoring the development of an exploratory code employing implicit differencing and including the effects of thermal diffusion, momentum addition, and rotation. Such a code would allow a quite general exploration of coronal energetics. Ultimately, models must also be extended to fully three-dimensional calculations for at least a few special cases, but it is too much to ask that this be done immediately with our sparse present knowledge of coronal dynamics.

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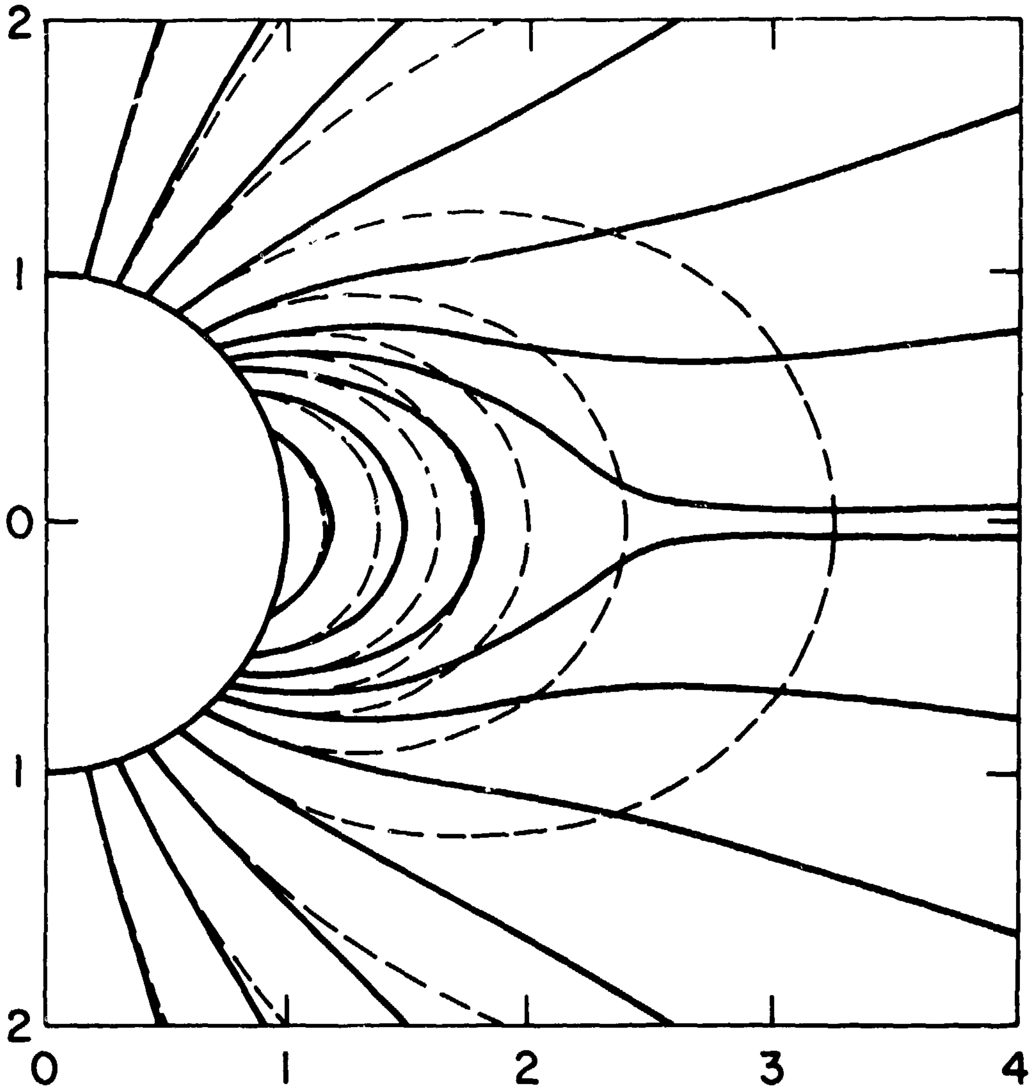

Fig. 1 Magnetic fieldline geometry (solid lines) completed by Pneuman and Kopp (1971) for a dipolar surface field of 1 gauss at the poles surface temperature of 1.5 x 10^6 °K, surface density of 10^8 cm^{-3}, and isothermal flow in the 1 to 5 solar radii range.

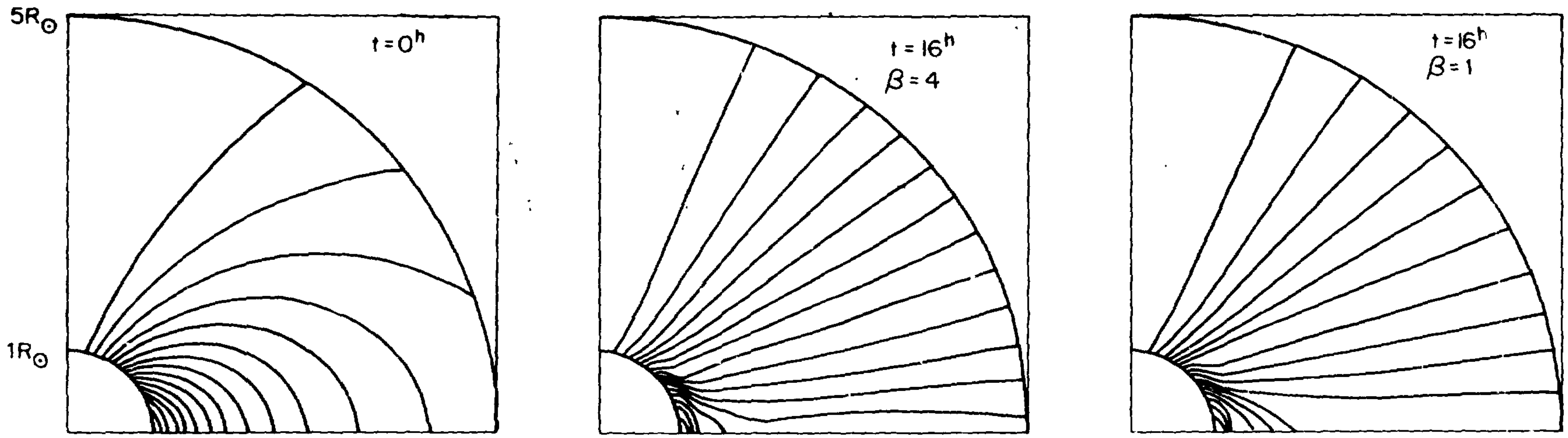

Fig. 2 Left: The initial state for the fieldlines which are then allowed to relax through dynamic interaction with the solar wind to the final states shown in the middle and bottom panels. This initial state is a pure vector dipole. Middle: Final state after a dynamical time of 16 hours, for a plasma beta at the surface and equator of the sun of 1—corresponding to a surface field strength of 1.66 gauss. Right: Final state after a dynamical time of 16 hours, for a plasma beta at the surface of the sun and equator of 4—corresponding to a surface field strength of 0.83 gauss. In all three panels, the plotted fieldlines begin at the same latitudes so that their footpoints and intersection points with the circle at 5 solar radii can be directly intercompared.

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The Contraction and Disappearance of the Polar Coronal Holes

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ABSTRACT

He I 10830 Å spectroheliograms obtained routinely during 1974-1979 have been used to study the evolution of the Sun's polar coronal holes. Synoptic polar plots show that the holes have decreased in size to the point that only vestigual holes remain and even these remnants fluctuate with detailed sunspot activity. During 1977.5-1979, the area of each hole fell from 8% x $4\pi R^2$ to less than 2% x $4\pi R^2$ at the areal rate of 1.0×10^4 km^2/sec.

I. Introduction

Several previous studies have indicated that the sizes of the polar coronal holes vary during the sunspot cycle. Some of these studies have been based on synoptic ground-based coronagraph observations (Waldmeier, 1951) or on isolated X-ray and XUV observations (Muney and Underwood, 1968; Broussard et al, 1978). Others have been based on well-understood properties of coronal holes together with an empirical knowledge of the sunspot magnetic cycle (Hundhausen, 1977; Bohlin and Sheeley, 1978; Harvey and Sheeley, 1979).

In principle, the evolution of the polar holes should reflect the variation of the polar magnetic fields in which these holes are located. At sunspot minimum when the polar fields are strong, the polar holes should be relatively large and symmetric. Near sunspot maximum when the polar fields weaken and reverse, the polar holes should contract and disappear.

This paper concerns the evolution of the polar holes during the five-year, post-Skylab period 1974-1979. This interval includes the relatively quiet years around sunspot minimum (1976) when the polar holes should have been large, as well as the increasingly active years (1977.5-1979) when the polar holes should have been contracting. Consequently, observations during this interval provide a test of our present understanding of the evolution of the polar coronal holes.

Polar coronal holes are visible on He I 10830Å spectroheliograms that have been obtained almost daily at the Kitt Peak National Observatory (KPNO) since February 1974 (cf. Harvey et al., 1974, 1975; Livingston et al., 1976; Harvey and Sheeley, 1977, 1979; Sheeley and Harvey, 1978). At KPNO, these helium images have been used to construct synoptic maps of coronal holes routinely since January 1977 (Solar-Geophysical Data 1977-1979) and occasionally prior to that time. The measurements described in this paper are based on these synoptic maps.

2. Data Reduction Techniques

The polar coronal holes were transferred from the rectangular synoptic charts to polar coordinate maps in order to improve their visualization. In each hemisphere, the direction of the azimuthal coordinate was chosen to give the image the same parity that it would have if it were viewed from above the pole. However, in this presentation, the size of each hole is somewhat smaller (relative to the full disk) than it would appear from above the pole because the radial coordinate is linear with respect to solar colatitude rather than with respect to the sine of the colatitude.

The polar holes have been plotted as they would appear in a coordinate system whose synodic rotation period is 30 days rather than approximately 27 days. This 30-day period was chosen empirically so that long-lived, high-latitude lobes of the polar holes would remain stationary on consecutive rotations. Of course, this transformation produced a loss of synchronization with respect to the Carrington system because slightly more than one synoptic map was required to construct each polar plot.

Finally, these plots were used to derive the solar surface area of each polar hole. This area was determined by integrating the areal element, $R^2 \sin\theta \, d\theta \, d\varphi$ (θ and φ are colatitude and azimuth, respectively), over the region within the boundary of each polar hole. In practice, the θ-integration was performed first, and the resulting function of φ was integrated numerically at 18° intervals around the boundary of the hole. Finally this surface area was expressed in units of the surface area of the spherical Sun ($4\pi R^2$).

3. Results

Figure 1 is a sample of polar plots for the equinoctal seasons of 1975 and 1978. The surface area of each hole is indicated as a percentage of the surface area of the Sun ($4\pi R^2$). A seasonal effect seems to be present in the sense that each polar hole is largest at the time of the year that it is most visible from the Earth. Thus, during 1975 the north polar hole is larger in October than in April and the south polar hole is larger in April than in October. This same result holds in 1978 for the months of March and September. However, as we shall see later, the magnitude of this effect is comparable to the variations of polar cap area that occur naturally in a duration of a few to several months. Consequently, this result may seem more convincing than it really is (despite the fact that the plots were not selected to advocate a seasonal effect).

The most significant aspect of Figure 1 is the fact that in 1978 the polar holes are much smaller than they were in 1975. Furthermore, in 1978 they seem less inclined to occur at the poles themselves. Although large lobes did occur in 1975, they extended equatorward from relatively large holes that were more-or-less centered on the poles. In contrast, during 1978 most of the coronal hole area seems to be confined to lobes and relatively little encircles the poles. In September 1978, the south pole lay just outside of the "polar hole". This effect was not an isolated incident that could be attributed to measurement error because it occurred on several consecutive months in the southern hemisphere, as well as at other times in the northern hemisphere.

Figure 2 presents all of these measurements of polar hole area together with the previous measurements of Bohlin (1977) and Broussard et al. (1978). Bohlin used synoptic He II 304Å images obtained during the Skylab mission to construct polar plots whose area be measured and expressed in units of $4\pi R^2$. Broussard et al. measured the visible surface area of polar holes on isolated X-ray and XUV images, but expressed these "half areas" in terms of $2\pi R^2$. Consequently, all of these measurements should be approximately comparable with the possible exception of Broussard et al's high-latitude, but non-polar holes (solid squares). Assuming that these holes were entirely visible in the X-ray and XUV images, their areas should have been expressed in units of $4\pi R^2$ rather than $2\pi R^2$ to be comparable to the other measurements. Thus, in Figure 2 the areas of Broussard et al.'s high-latitude holes (solid squares) probably should be reduced by a factor of one half.

In Figure 2, one can see that the areas of the polar holes have decreased considerably from their Skylab-era values of approximately 8%. A linear fit to the measurements during 1977-1978 indicates a rate of decrease of approximately 5%/year in each hemisphere corresponding to an areal decrease of $(1.0 \pm 0.1) \times 10^4$ km^2/sec. In each case, the projected time of zero area is early 1979.

On the right side of Figure 2. the scale refers to the latitude at which the boundary of each hole would lie if the area of this hole were distributed symmetrically about the pole. Although this equivalent latitude was approximately 60° in the quiet years near sunspot minimum (1976), it exceeded 70° toward the end of 1978. Of course, the concept of equivalent latitude may not be useful for the recent holes because their irregular shapes differ greatly from that of a classic polar cap.

In Figure 2 the helium measurements have a rather large scatter of roughly 2-3%. As we have discussed earlier, part of this variation may be a visibility effect associated with the changing heliographic latitude of the Earth during the year. However, an equally large part of it is also due to real short-term changes of polar hole area. Such changes typically occurred as lower-latitude holes formed and temporarily merged with the polar holes. The areas of such lobes were included as part of the areas of the polar holes. Although this effect was relatively unimportant when the polar holes were large, it is particularly serious now that they are small. Indeed, Broussard <u>et al</u>. (1978) found that such non-polar holes were the main source of high-latitude coronal hole area during this phase of the previous sunspot cycle (square data points in Figure 2).

4. Discussion

The measurements in Figure 2 continue to support our expectation that the polar coronal holes vary during the sunspot cycle. The formation of these holes in 1972-73 during the declining phase of the cycle has been discussed extensively in several studies of the Skylab and OSO-7 observations (cf. Bohlin and Sheeley, 1978, and references contained therein). In effect, the formation of the polar holes resulted from the increasing magnitude of the polar field strengths together with the decreasing influence of active regions. By 1972-1973 each polar cap had apparently accumulated enough unipolar magnetic flux to satisfy the connection requirements of nearby magnetic regions and still to have unbalanced flux left over to form a hole.

In this paper we shall consider the inverse process in an attempt to understand the contraction of the polar holes during 1977-1978. Since sunspot minimum in 1976 the influence of active regions has been increasing and presumably the polar magnetic field strengths have been decreasing. Apparently by 1978 the polar caps no longer had enough unipolar magnetic flux to always satisfy the connection requirements of nearby magnetic regions and still to have enough unbalanced flux left over to form large polar holes. The north polar hole almost vanished in January 1978 (0.4%) and the south polar hole nearly vanished in August (0.1%) and September (0.6%).

The fact that these near-vanishings have been short-lived indicates that they have been caused by short-term changes in the nearby magnetic regions rather than by a reversal of the polar fields themselves (which incidently have not yet reversed). Presumably these intermittent vanishings will occur for progressively longer intervals until the polar fields themselves reverse. Then the location of high-latitude holes will be determined entirely by the distribution of flux that is diffusing poleward from the sunspot belts.

Finally, it is interesting to note that while short-term variations of the polar holes accompanied the fluctuations of nearby lower-latitude fields, the long-term contraction of the polar holes occurred at a well-defined rate of $(1.0\pm0.1)\times10^4$ km^2/sec. This rate is comparable to the values of 1.5×10^4 km/sec and 0.8×10^4 km/sec obtained by Bohlin (1977) and Nolte _et al_. (1978), respectively, for Skylab observations of coronal holes. It is also comparable to Leighton's (1964) rate for the dispersal of magnetic flux (1.0×10^4 km^2/sec) as well as to Mosher's (1977) correction (0.5×10^4 km^2/sec) to this rate.

Despite the encouraging order-of-magnitude agreement between these measurements, it is still not obvious that the polar holes should close at the areal rate of magnetic flux transport. Rather, the rate should depend on the rate of change of open flux in the polar cap. In turn, this flux rate should depend on the location, magnitude, and occurrence rate of the low-latitude flux sources as well on the areal rate with which it diffuses. All of these factors must be considered before even this rudimentary aspect of the problem can be understood quantitatively.

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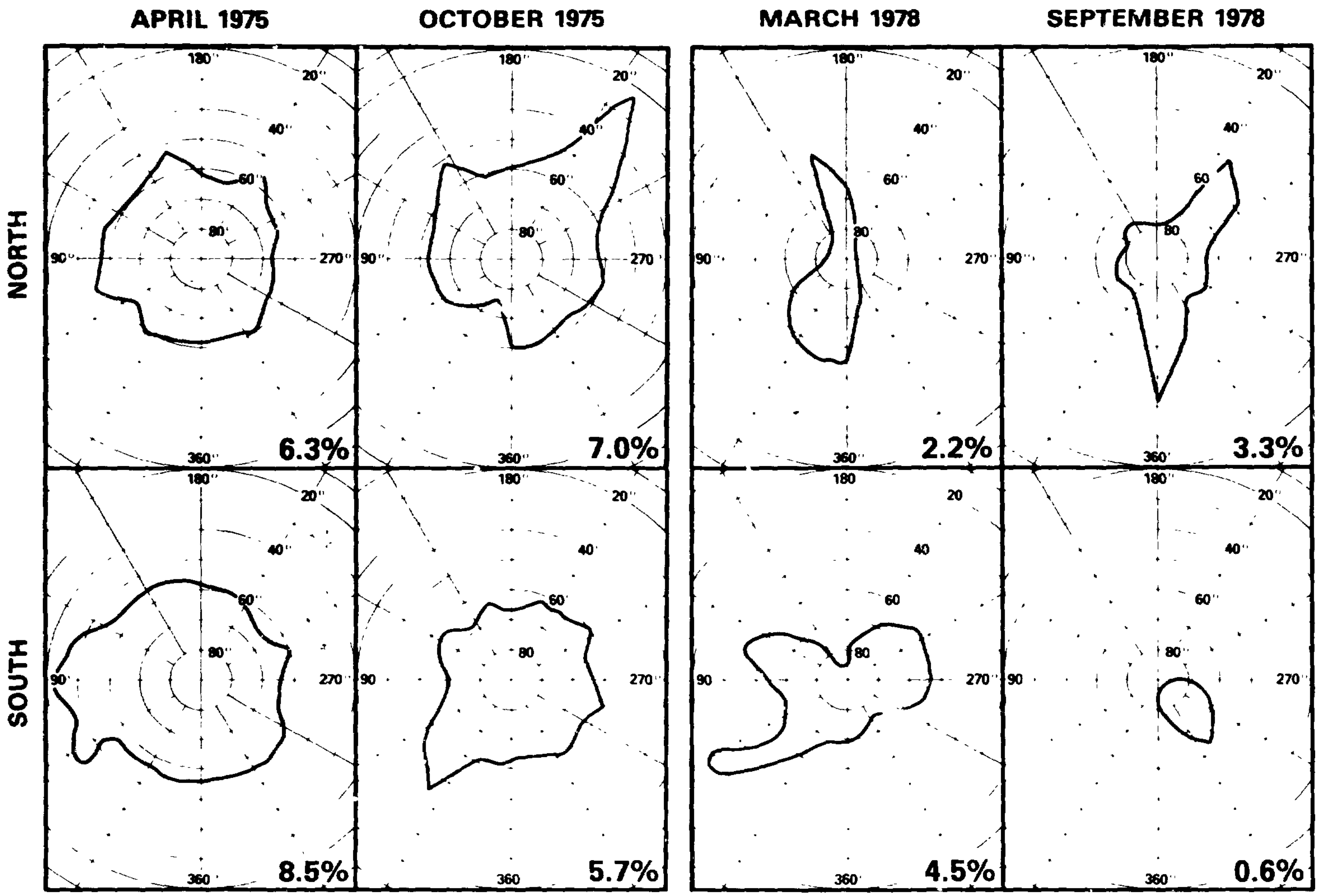

Fig. 1: A sample of polar plots illustrating the fact that the polar coronal holes were smaller and less confined to the poles in 1978 than in 1975. The surface area of each hole is indicated as a percentage of the surface area of the Sun ($4 \pi R^2$).

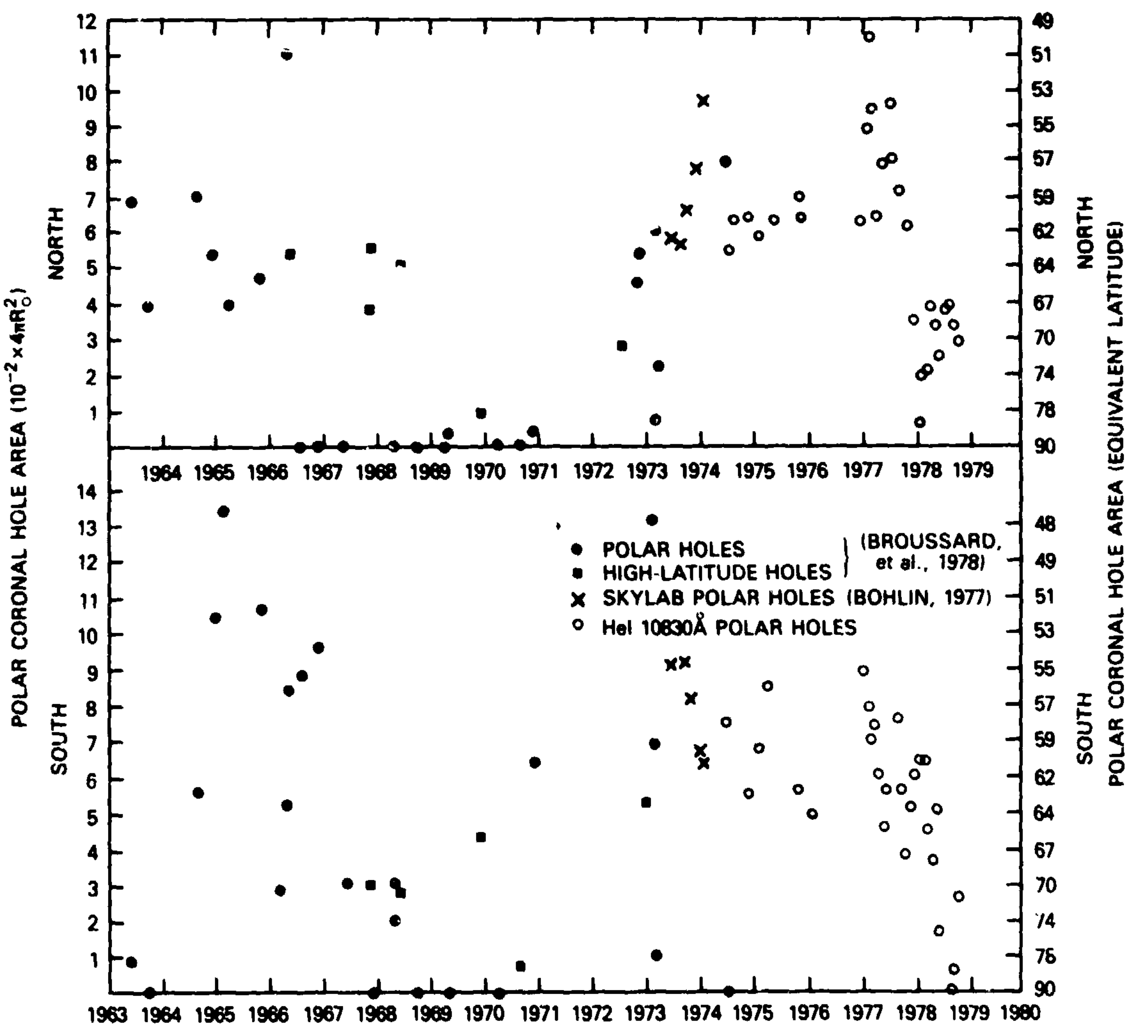

Fig. 2: Measurements of the areas of polar holes during 1963-1979. The measurements of this paper (open circles) are combined with measurements by Bohlin (1977) and Broussard *et al*. (1978) to indicate the long-term trend.

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Solar Cycle Changes in the High Latitude Solar Wind

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Abstract

Measurements of the solar wind speed by the technique of interplanetary scintillation are presented for 1971-79. The average wind speed was faster than 500 km/s at latitudes above ± 30° for most of 1973-77. This fast polar stream, however, was observed to become much narrower in 1978-79. The narrowing of the polar streams coincided with the emergence of sunspots at mid-latitudes, with the start of the new solar cycle, and with a corresponding contraction of the polar coronal holes. This result supports the idea that the solar magnetic field controls the large scale structure of the solar wind.

It has long been known that the solar wind cannot be spherically symmetric although, perforce, this simple model has often been used. The most obvious structures are the fast streams which are now known to have steep spatial gradients both in longitude and latitude (e.g. Hundhausen 1977). We present here measurements of the latitude structure of the solar wind speed from 1971 to 1979, made using interplanetary scintillations (IPS). The results show that persistent high speed streams emanate from the poles of the sun; and that these streams are modulated by the solar cycle exactly as are the polar coronal holes.

The IPS technique has been discussed by many authors (Dennison and Hewish 1967, Armstrong and Coles 1972, Watanabe et al. 1973). Our 74 MHz observatory at San Diego and its data analysis are described by Coles and Kaufman (1978). IPS observations in the ecliptic have been compared with direct spacecraft measurements (Coles et al. 1978). That work gave a 'calibration' of the simple interpretation, which we adopt here, that the IPS method estimates the solar wind speed at the point where the maximum scattering occurs. We make IPS observations of eight radio sources daily, from which we typically obtain useful solar wind speed estimates at three to five such effective locations. The heliographic latitude of these locations spans 60°S to 70°N. However, the coverage is not continuous; northern latitudes (> 20°) are observed from March-July and October-November, while southern latitudes (> 20°) are observed June-July, each year (see Fig. 1 of Coles and Rickett 1979).

The solar wind speed can be averaged over longitude to provide the speed versus latitude plots of Figure 1. The characteristic U-shape has been described by Coles and Rickett (1976). This phenomenon is best described as evidence for persistent fast streams from the north and south poles of the sun. These polar streams are the solar wind response to the polar coronal holes, in just the same way that ecliptic streams originate from low latitude coronal holes.

Long-term changes in the polar streams can be seen in Figure 1. We identify three phases.

First, 1973-75 shows stable co-rotating structures with two "polar" streams tilted about 30° from the rotation axis, as revealed in Figure 2 (Sime and Rickett 1976). The major coronal holes at this time can similarly be described as tilted polar holes; Figure 3 shows one estimate of the large coronal hole boundaries, revealing holes well aligned with the streams shown in Figure 2. Indeed the increased average speed at the equator in 1974 (Figure 1) is due to these streams, as discussed in the paper by Hundhausen (see this volume).

The second phase, 1976-77, during which solar activity is near minimum, shows polar streams that have widened and are better aligned with the rotation axis. This gives a steep average latitude gradient between 15° and 30° (over 10 km/s per degree) comparable with instantaneous measurements of the latitude gradient made by spacecraft (Smith and Rhodes 1974).

The third phase, 1978-79, occurs at the start of the new cycle of solar activity and shows a dramatic decrease in the speed at 30-60°N, with similar changes in the south. In other words the polar streams are narrowing at the same time that the new sunspots are emerging at mid-latitudes. This change evidently occurred at the same phase during the previous cycle. The change that we observed between 1977 and 1978 was seen by Hewish and Symonds (1969) between 1966 and 1967. However, they observed only for two months of these two years and so were unable to draw any strong conclusions.

The presence of mid-latitude sunspots implies that bipolar magnetic regions are dominating these latitudes, restricting the area of open fields (i.e. the polar coronal holes). Evidence for the reduced area of the polar holes was given by Sheeley in the previous paper (see this volume). Figure 4 shows a comparison of average wind speed at 0, 30°, 60°N with the area of the north polar hole from 1971-79. Hole area estimates from Kitt Peak He 10830 Å data are plotted for 1974-78 together with earlier estimates from a variety of techniques. The slowing of the wind at 30° and 60°N in late 1977 to the present is closely matched by the shrinking of the north polar hole.

Figure 5 shows the comparison as a plot of latitude versus time. The continuous line in the north and horizontal bars in the south represent the boundaries between fast and slow wind from six-month averages of wind speed. They can be viewed as average boundaries of the polar streams in the north and south. The dramatic change occurs between the period 1974 to early 1977 and the period late 1977 to the present. In the earlier period the boundary is near ± 30°, showing that the fast polar streams filled 50% of the total 4π steradians; while in the recent period the boundary moved up to near ± 65°, showing that the polar stream now fills only 9% of 4π steradians. This is similar to the situation in 1971, although our data coverage for that year is poor. The various symbols identify the polar hole boundaries (on the assumption of axial symmetry). Although there are real rotation to rotation changes, the long-term behavior can be described as a 60°

boundary (13% solid angle for north plus south hole) in 1974-77, followed by a retreat to 70° (6% of solid angle) in mid-1978.

We may define a solid angle expansion ratio between the (arbitrary) 500 km/s wind speed solid angle and the solid angle defined by the He 10830 Å holes. This ratio decreased from 3.8 for the earlier period to 1.5 for 1978. Whereas the numerical value of this ratio cannot easily be related to the areal expansion factor as defined for the northern polar hole by Munro and Jackson (1977), the change in our ratio shows that the areal expansion factor of the polar holes decreased substantially as the holes shrunk.

In summary we have observed that the polar streams have narrowed substantially, at the same time that the polar holes have narrowed. This result reconfirms the importance of the solar magnetic field in controlling the corona and solar wind. It is likely that this changing three-dimensional structure determines the solar cycle modulation of cosmic rays. From the viewpoint of SCADM, it is clear that the high latitude solar wind shows a more pronounced solar cycle dependence than does the ecliptic solar wind, and should be monitored together with the sun and ecliptic solar wind. Equally important, the detailed information on the latitude structure to be obtained from the Solar Polar Mission must be viewed in the context of the long-term evolution as presented here.

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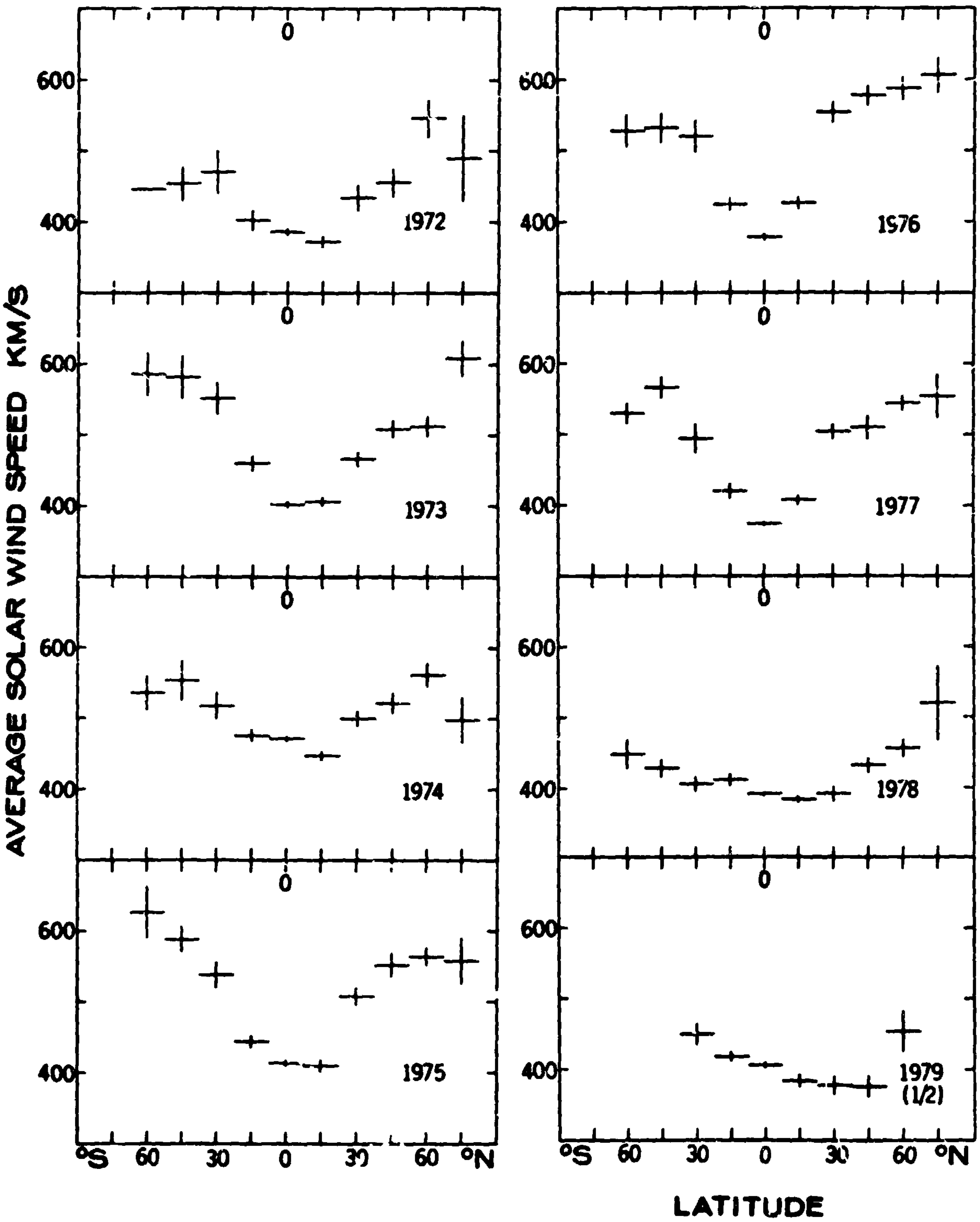

Figure 1. Solar wind speed measured by IPS averaged into 15° intervals in heliographic latitude for the years 1972-1978 and January-June 1979. The error bars are ± twice the standard deviation in the average.

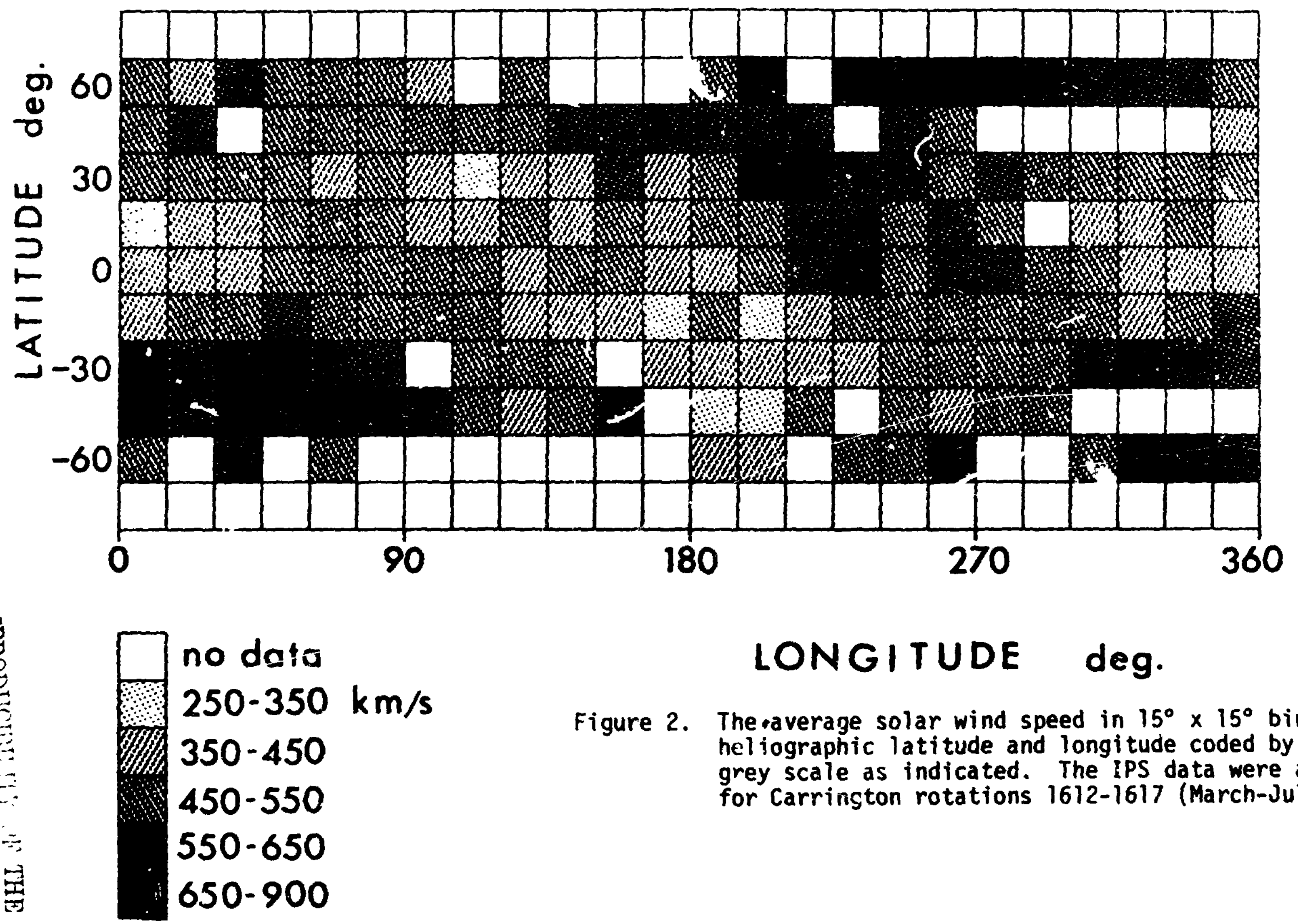

Figure 2. The average solar wind speed in 15° x 15° bins of heliographic latitude and longitude coded by the grey scale as indicated. The IPS data were averaged for Carrington rotations 1612-1617 (March-July 1974).

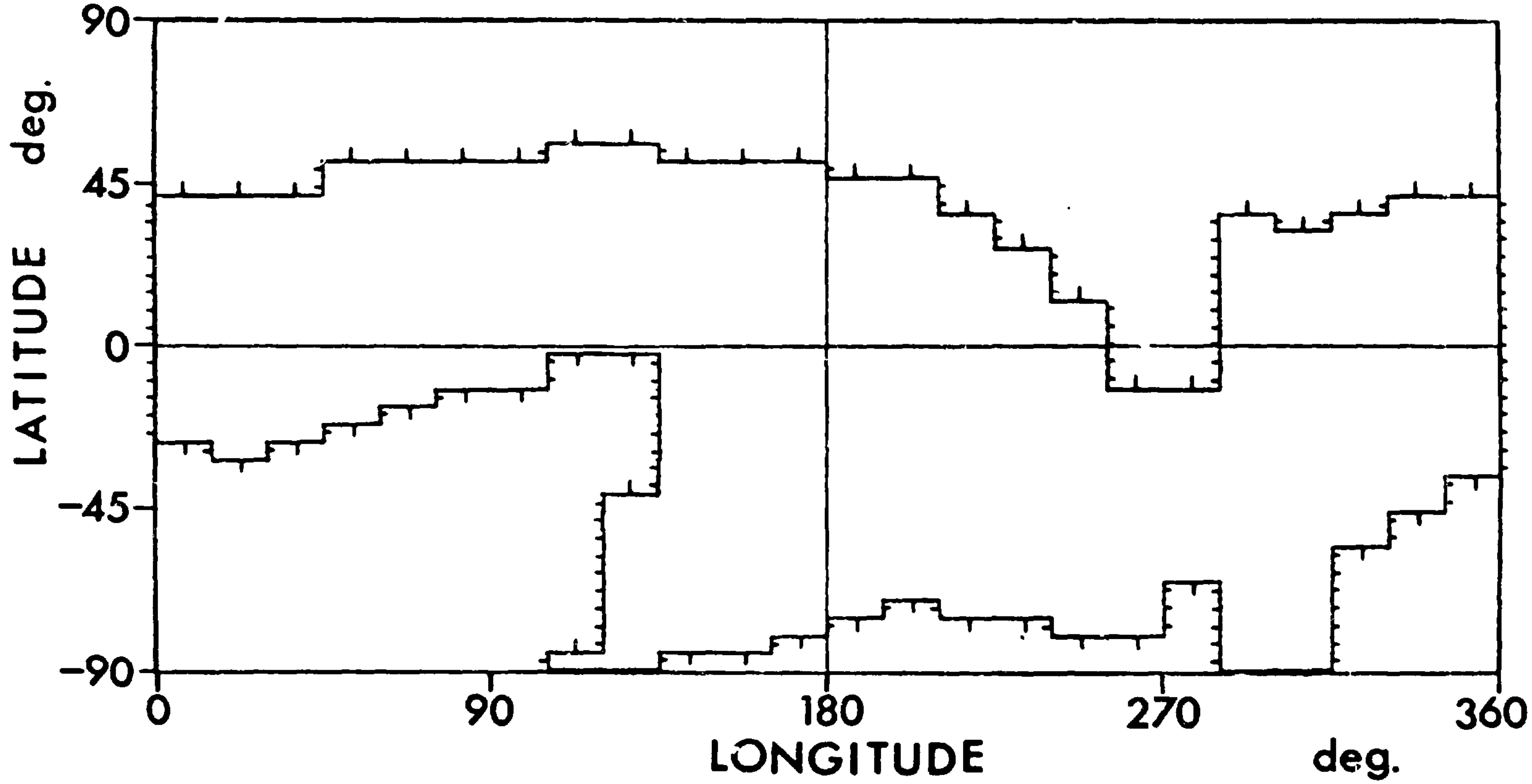

Figure 3. Coronal holes indicated by a contour of low K-coronameter brightness (1.5 x 10^{-8} pB); the tick marks point toward low brightness, i.e. toward the holes. Data supplied by Drs. R. and S. Hansen (H.A.O.).

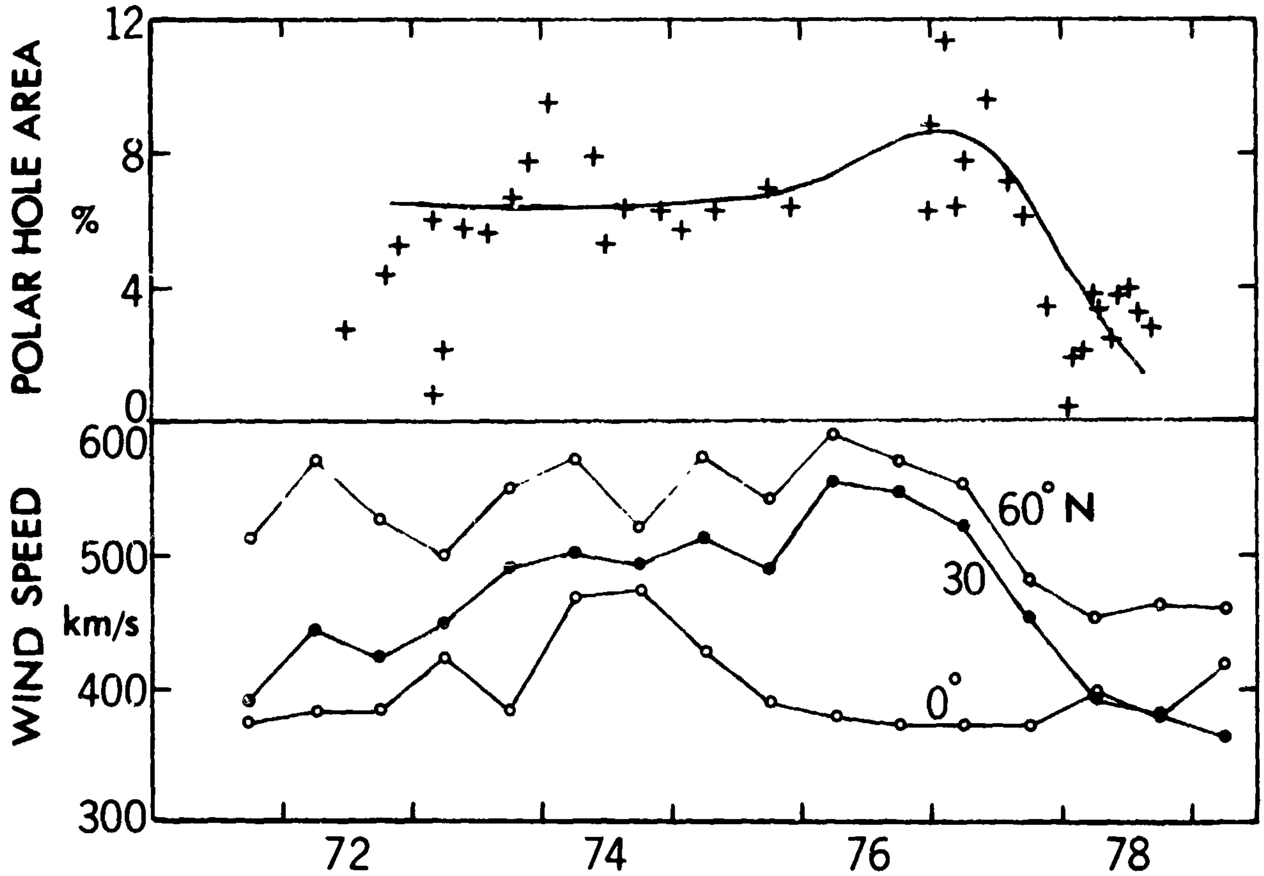

Figure 4. North polar hole area as percentage of solar surface (Sheeley, 1979); curve is drawn by eye. Solar wind speed from IPS observations averaged over six months and 15° in latitude centered on the latitudes indicated.

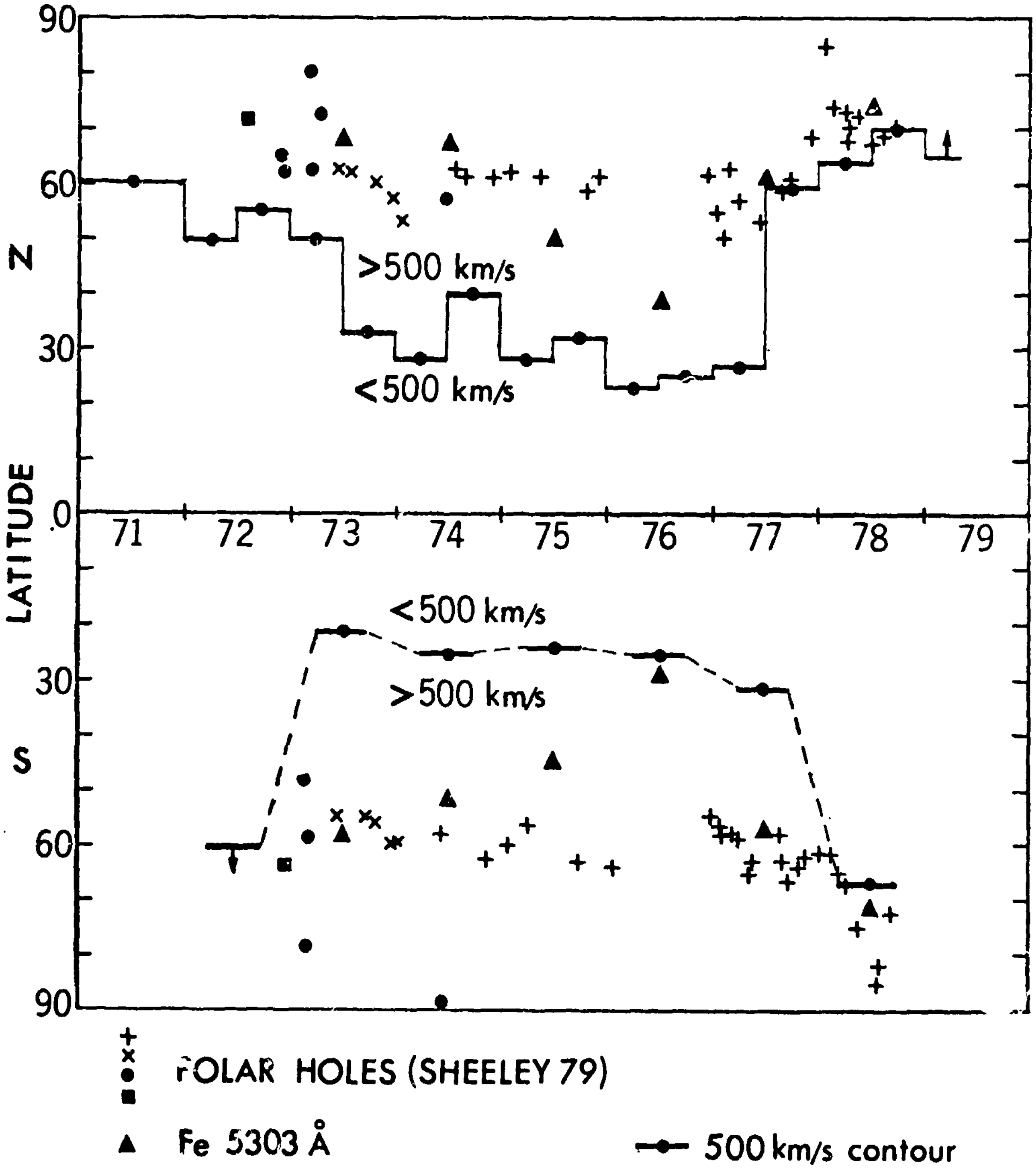

Figure 5. Solid curve (in the north) and horizontal bars (in the south) indicate the contour of 500 km/s average solar wind speed. The latitude boundaries of the polar holes are indicated by various symbols: + He 10830 Å, × Bohlin (1977), ● ■ Broussard et al. (1978), ▲ Fe 5303 Å (threshold at 1.5 x 10-6 of disc center brightness, data from Sacramento Peak Observatory).

AN IMAGING X-RAY SPECTROMETER TO STUDY SOLAR ACTIVITY IN CONJUNCTION WITH THE SCADM PROGRAM

New Instrument Contribution for the
Symposium on the Solar Cycle and Dynamics Mission

by Richard L. Blake, LASL

I. Introduction

Processes in the deep convective zone beneath the solar photosphere are responsible for solar activity. Aside from recent developments in solar seismology and luminosity measurements, our ability to model the convection zone processes must be evaluated against observations of phenomena at or above the photosphere. It behooves us to make the best possible observations that are directly relevant to dynamo models. We believe the instrument suggested in this paper is one of the best presently possible for studies of dynamic solar activity processes. While there is no compelling reason for placing this experiment on a special SCADM satellite platform, it should be operated from some space platform at selected intervals over the SCADM lifetime. The Space Shuttle is a possible choice, although a less severe thermal environment would reduce costs.

An experiment is proposed to study solar active region dynamics and evolution. It will greatly extend the range of capabilities provided by the Solar Maximum Mission (SMM). The larger volume and weight capacity of a Shuttle launch make possible an experiment with enough sensitivity to study the fastest known solar phenomena with high spatial and spectral resolution. We shall be able to utilize a spectral resolving power $\lambda/\delta\lambda \sim 3 \times 10^4$ to image events on a scale as small as 5" in time intervals as short as 10^{-3} seconds. It will be possible to use this tremendous diagnostic power from the instant of event onset. Similar sensitivity will be available for the study of active region morphology and evolution.

Because this experiment has such high capacity for simultaneous high resolution imaging, spectral dispersion, and time resolution it comes as close as one can presently get to the observational requirements to completely characterize complex dynamic events. The observational modes include:

(1) line profile analysis
(2) complete or partial spectral scans
(3) simultaneous observation of the red and blue wings of a line to detect dynamic plasma processes
(4) spectroheliograms
(5) polychromatic monitoring
(6) sensitive polarimetry of lines and/or continuum.

Data from this investigation should prove invaluable to the scientific objective of understanding the processes involved in the buildup and release of energy in the solar corona. Similarly, these data will be of the quality needed to answer key questions about solar composition and solar-terrestrial relations. Thorough in-flight calibration is incorporated to insure the data reliability.

The proposed Spectrometer Imaging X-Rays (SIX) is a first stage in the development of a large X-Ray Imaging Spectrometer-Polychromator (XRISP), which we proposed two years ago. Although XRISP was recognized as a major advance in solar physics instrumentation, it was also a very expensive system whose ultimate implementation might fall in the multi-user instrument category. The SIX has been conceived around the following basic criteria:

(1) Retain the essential features of XRISP while striving for a lower cost approach in the PI instrument class.

(2) Make the lower cost version compatible with an evolutionary program that starts with SIX in several early Spacelab flights (1983), followed by additions over the period around solar minimum (1984-86) to bring the system up to the XRISP level, further XRISP-level flights on Spacelab in the next buildup of solar activity (1987-88), and finally a free-flyer including XRISP for the next solar maximum period 1989-92.

(3) Make the instrument reasonably self-contained so that it can fly either as part of a multi-disciplinary mission or in a dedicated solar physics mission.

(4) Keep the program management options open to possible evolution into a multi-user facility.

Criterion 2, the evolutionary approach, can be met in several ways. With SIX we are at the full size of the eventual XRISP, but with less subsystems and all parts well within the state of the art. The evolutionary scheme is also set up so that NASA can choose to fund one piece at a time instead of committing to a 15 year program all at once.

The following tabular summary covers the main SIX experiment characteristics.

EXPERIMENT SUMMARY

Title: Spectrometer Imaging X-Rays (SIX)
Spectral Range: 1 - 100 A
Spectral Resolution: $\lambda/\delta\lambda$ up to 3×10^4
Field of View: 30" by 100" and 15" by 1[illegible]"
Angular Resolution: 10" x 10" and 5" by [illegible]"
Time Resolution: 10^{-3} s
Size: 1.3m x 1.3m x 3m
Collecting Area: Total - 3600 cm^2
Area for distinguishing a point source - 162 $cm^2 \times \Omega$
Area for spectrophotometry of a point source - 837 $cm^2 \times \Omega$
Ω (Product of geometrical throughput and detector efficiency) $\sim$ 0.15
Sensitivity: Signal to noise ratio will be about unity for a flux $\sim$1 ph cm^{-2} sec^{-1} at 1 AU in the 1.9 A Fe XXV resonance line;source can be either a point source or extended.
Dynamic Range: 10^5 on MECAs; 10^6 on SECA
Weight: 550 kg
Power: 134 W average; 242 W peak
TM: HRM 798 kbps in flare mode
1.5 kbps in active region mode (non-flare)
RAU 5 kbps
Video 4 MHz S band
Primary Instruments: Three collimated plane-crystal spectrometers
Detector Type: Simple proportional counters

Special Features: Imaging with 5" resolution and very high spectral resolution
Plasma dynamics analysis from simultaneous observations in red and blue wings of any line in spectrum from 1 to 15 A.
Very fast time resolution.
Expandable to greater capacity in evolutionary approach.

II. Objectives

(a) Scientific

(1) Isolate and characterize the physical processes involved in build up and release of energy in the solar corona, especially in flares and active regions.
(2) Determine the solar element abundances in the corona and whether they vary in time, location on the disk, or in association with solar wind streams.
(3) Discover any new aspects of the solar activity cycle that could help to explain the correlations with terrestrial phenomena.
(4) Evaluate models of the corona, such as the recent loop models of Rosner et al. (1978) and Ionson (1978).

(b) Intermediate "Model Parameters" to be Measured

(1) Wave motions -- periods, amplitudes, spatial distribution.
(2) Shock propagation - risetime, decay time, energy content and dissipation, spatial distribution.
(3) Non-propagating pulsations - time scale, spatial distribution, energy content.
(4) Suprathermal plasma - distribution functions in space, time, density, and energy for electrons and ions.
(5) Thermal plasma - distribution functions in space, time, density, and energy for electrons and ions.
(6) Macroscopic parameters - electron temperature and density, ion temperature and density, turbulence parameters, and emission measures.

(c) Observational Capabilities Meeting Requirements of (a) and (b)

(1) Wavelengths of lines accurate to a few parts in 10^6.
(2) Spectral resolution 3 to 10 times narrower than anticipated Doppler widths; $\lambda/\delta\lambda \sim 7 \times 10^3$ to 3×10^4.
(3) Best attainable spatial resolution; 5" x 5".
(4) Imaging simultaneous with above capabilities.
(5) Temporal resolution simultaneous with above; 10^{-3} seconds.
(6) Simultaneous observation of 3 lines, arbitrarily chosen anywhere in range of observation 1-100 A.
(7) Choice of continuum monitoring instead of lines.
(8) Simultaneous observation of two sides of a single line, with wide range of choice on any line to be observed in the 1-15 A range.
(9) Signal to noise dynamic range of 10^5.
(10) Timing accuracy of 10^{-3} seconds.
(11) Calibration accuracy to ±10 percent on intensities and two arc seconds on solar locations (built into experiment).
(12) Polarization sensitivity of better than one percent on lines <u>or</u> continua (2 to 10 keV) in time it takes IPS to rotate 180 degrees.
(13) Thorough inflight calibration.

III. Approach

(a) Concept

Our guiding idea has been to choose the approach that quantitative comparisons have shown to be most sensitive to dynamic events. We had to find a way to simultaneously image solar phenomena while employing high resolution spectroscopy to diagnose the physical processes. The time resolution was just a matter of experiment size.

Possible approaches include (1) plane crystal spectrometers preceded by imaging collimators, (2) plane crystal instruments with pencil beam collimators that are rastered, (3) convex curved crystals, (4) concave curved crystals behind an x-ray telescope, and (5) objective grating telescopes. Method (1) is our approach. The second is too slow because of the raster needed to make an image. The third provides no imaging and low sensitivity. The fourth is too slow because of the raster requirement and is also mechanically complicated, expensive, and not effective at the wavelengths of most interest ~ 2 A. (Method (4) is probably the best at long wavelengths, especially for long term evolution of the solar corona.) Method (5) is the only viable competitor to (1) for our objectives. We reject it because it has very low efficiency at ~ 2 A where method (1) is strongest and because the presently attainable resolving power is not high enough.

Observations of dynamic events like solar flares are essentially signal limited rather than background limited. That is, one must provide sufficient collecting area to assure a statistically significant number of photons in the event time scale. Only then do background considerations need be made. This factor works against method (5) and in favor of (1) at short wavelength. Hadamard transform spectrometers (Miyamoto, 1977) are also ruled out for this and other compelling reasons.

A very strong influence on our choice has been made by the scientific need to determine types of plasma motions involved in dynamic solar events. Such fluid motion analysis demands very rapid observation of changes in line profiles over spatially extended regions. Our approach is very powerful for this purpose, having in fact been taken from well established optical techniques.

(b) Method

Simultaneous spectroscopy and imaging of dynamic solar x-ray sources can be achieved most efficiently by crystal spectrometers preceded by imaging multielement collimator arrays (MECA). As seen in Figure 1 each MECA element (subcollimator) is physically separate from its neighbor, the two of which can be designed to view separate locations on the solar disk. Numerous MECA elements may be combined into a single housing so as to cover an appropriate region of the solar disk (Van Beek, 1976). Behind each MECA element is a separate crystal whose orientation is shifted relative to its neighbor in amount equal to the angle $\Delta\theta$ between the corresponding two MECA elements - this permits both crystals to observe the same wavelength λ_o but from different solar locations. A separate detector element for each combination of crystal and MECA element permits electronic synthesis of the signals to generate a spectroheliogram at the wavelength setting of the system. To change wavelengths the entire crystal array is rotated and the Bragg relation holds; i.e., $n\lambda_o = 2d \sin\theta_o$, where θ_o is the angle between any MECA element axis and its crystal surface.

Ideally one would like to employ enough MECA elements to cover the entire sun with one arc second resolution. In practice the diffraction of x-rays in the grids making up a MECA element limits the resolution to 3", and physical constraints prevent whole sun coverage even at 3" resolution. Our approach is to

(1) Provide spatial resolution in two steps of 5" and 10" by means of nested MECA systems (Figure 2). Increments chosen are compatible with diffraction limits for the wavelengths to be observed and with grid collimator technology.
(2) Provide true imaging at 5" resolution over a FOV 15" x 15", and at 10" resolution over a FOV 30" x 100", by means of MECA spectrometers.

We believe this approach suffers little relative to the unattainable ideal because of the following factors:

(1) With the aid of coordinated ground observations our field of view will include the entire area of the majority of x-ray flares in a selected active region and only about half the total number of solar flares will be missed because of the pre-selected active region being the wrong one.
(2) It permits unambiguous location of point sources in 1 sec of time,
(3) It permits one to follow precisely the evolution of a source that changes spatial scale in time,
(4) The hottest and brightest region, i.e. a hot core where the energy input is suspected to occur in impulsive flares, is selected for immediate high resolution spectroscopic diagnostics, and
(5) Extended sources can be imaged, along with high resolution spectroscopy.

Figure 2 illustrates the nested MECA approach for SIX (figure 3 is a probable nested MECA approach when SIX evolves into XRISP). Imagine one bank of crystals (say one of the two identical side banks in figure 4) fed by a MECA in which each pixel is 10" x 10" and the FOV is 30" x 100". Then consider a separate bank of crystals (the centrally located bank in figure 4) fed by another MECA, whose reference axis points in the same direction as the axis of the larger array but whose FOV is 15" x 15" with 5" resolution per pixel. The second of the two identical side banks of crystals has a set of 10" resolution pixels whose field of view on the sun is exactly superposed on that of the first bank. The red and blue wings of a line are selected by shifting the crystal banks in opposite directions while holding the field of view fixed.

Whether one is observing a flare region or nonflare active region, the spectrometers can be set for the hottest line (or continuum) expected and one increment of the pointing control, taking 2 seconds of time, will be sufficient to place the 5" resolution spectrometer field of view onto the source of energy input in the solar atmosphere. Or the spectrometer array with 10" resolution can be used to monitor from the instant of flare onset.

It is important to realize that a "snapshot" in this scheme gives the full image of a flare and its surrounding active region with simultaneous high spectral resolution, albeit with highest spatial resolution only at the seat of energy input. If one does not insist on moving the 5" spectrometer FOV to the seat of energy input the flare event can be followed spectroscopically from its onset with 10^{-3} sec time resolution. Based on the statistics of soft x-ray flare sizes from the ATM program (Kahler, 1978) and the known preference for flares to develop along magnetic neutral lines, it should be possible to orient our rectangular field of view to cover the entire area of the majority of flares.

Polarization measurements with a sensitivity of one percent or better can be made in the time it takes to rotate the experiment around its line of sight by 180°. The crystals are nearly perfect polarizers near 45° Bragg angle. Any line or continuum near 45° can be measured.

Performance criteria for the instrument have been evaluated from existing knowledge of solar x-ray fluxes and temperatures folded into crystal diffraction theory. Crystals are available for line profile studies below 12.5 A and for line flux measurements up to 100 A. Mechanical stability requirements can be met by separating the collimators into a kinematically mounted housing with thermal and mechanical isolation from the remaining external coarse structure. Grids for the collimator are ava ле commercially as a result of developments in our rocket program. In fact, the only subsystem that has not been already developed and flight proven is the thermal control, and the technology for this is obviously not new.

Modes of operation include:

(1) high resolution spectra,
(2) line profiles,
(3) dynamic spectra (mass motions, waves, pulsations),
(4) spectroheliogram,
(5) polychromator,
(6) calibration, and
(7) aspect.

IV. Aspect Sensing and Calibration

Our aspect calibration mode by use of cosmic X-ray sources suggests the acquisition of SCO X-1 with an accuracy of 30 arc seconds to avoid loss of time hunting for it. To correlate ith optical and magnetographic observations we need to have our own internal optical images to a precision of 1 arc sec. Further we must know the relation between our x-ray and optical axes within i arc sec to make effective correlations. We have made the cost-effective choice of taking aspect calibration from a system developed in our rocket program, which has 2 arc sec accuracy, correctable to 1 arc sec.

The rocket system has a simple interference-type Hα filter in front of a simple telescope objective which forms a Hα sun image on a reticle. A transfer lens provides a magnified, erect solar image on a one inch vidicon tube. The Hα filter and vidicon tube designs have repeatedly survived rocket thermal and vibration tests that exceed Spacelab requirements. Figure 5 shows both the layout of the aspect system and the technique for aligning the optical and x-ray axes. Co-alignment of the optical and x-ray axes is a two step process. First a reference mirror is installed on the x-ray collimator structure with its normal parallel to the x-ray axis within one arc sec. This is achieved by optical means with the same optical setup used to align the grids themselves (Blake et al., 1976). Second the reticle is illuminated from the backside; the beam coming through the telescope objective is in turn imaged by an autocollimator which simultaneously views the collimator reference mirror. The reticle is adjusted until its image coincides with that from the collimator reference mirror within one arc sec. We have thoroughly explored all the idiosyncrasies of this method and learned how to handle them.

A simple multiplexer superimposes universal time (or spacecraft time if UT is not available on the Spacelab) onto the TV image which is then transmitted to ground and recorded on video tape. Coordinates of the x-ray emission line of sight relative to a sunspot pattern are thus known to within one arc sec for correlation with ground based and other space observations with one msec timing accuracy.

When the experiment line of sight is drifted across SCO X-1 not only is the angular response of each pixel measured but also the angular separations of all the pixels from one reference pixel that was used to align the TV axis.

V. Comparison With Other Solar X-Ray Experiments

A large increase in spectroscopic diagnostic capability is made possible by the large volume and weight capacity of the Space Shuttle. To give the reviewer a brief summary of how solar observations will be augmented we provide in Table 1 a capsule comparison. The XRP is the x-ray polychromator on the Solar Maximum Mission (SMM) and HXC is the hard x-ray collimator, also on SMM. The XRP does spectroscopy with a single 10" pixel while the HXC images over an active region dimension without doing spectroscopy. SIX is a combination of both functions with improved spatial resolution and much greater sensitivity. As SIX evolves into XRISP we will gain still more on spatial resolution, wider spectral coverage, a little larger field of view, a f·t whole-sun flare finder, and more complex mode sequencing during fast ·ents. The principal investigators on both SMM experiments are collaborators on the SIX (or XRISP), which is a next-generation instrument. The scientific team so far consists of L. W. Acton (Lockheed), R. L. Blake (Los Alamos), A. J. Burek (NBS), H. Hudson (UCSD), G. Hurford (Cal Tech), W. Neupert (Goddard), H. Van Beek (Utrecht), A. B. C. Walker (Stanford), and colleagues in these institutions. Others are invited to participate in what we consider to be a solar studies program of high potential and hopefully accessible to a wide range of solar physicists.

References

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4. Miyamoto, S. 1977, Space Science Instrumentation 3, 483.
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TABLE 1

SUMMARY OF KEY POINTS IN COMPARISON WITH
OTHER SOLAR X-RAY EXPERIMENTS

SYSTEM / FACTOR	XRISP	SIX	XRP	HXC
RESOLUTION	3"	5"	10"	8"
FIELD OF VIEW	3'x3' SPECTRA 36'x36' FLARE-FINDER	30"x100" NO FLARE-FINDER	10" NO FLARE-FINDER	8.[illegible]' C MECA 3.2' F MECA
DECONVOLUTION	NO ON SPECTRA YES ON FF	NO	---	NO ON MECA
IMAGE SUSCEPTIBLE TO TIME VARIATIONS	NO	NO	---	MILD
SPECTROSCOPY	YES	YES	YES	NO
SPECTROSCOPY SUSCEPTIBLE TO TIME VARIATIONS	ONLY ON VERY LARGE & COMPLEX SOURCES	ONLY ON VERY LARGE & COMPLEX SOURCES	YES, EXTREME	---
SENSITIVITY				
a. LOCATE A POINT SOURCE	94 (AT 3" RES.)	88	0	0.16 (AT 8" RES.)
b. Fe LINE SPECTROSCOPY	375 (AT 3" RES.) 711 (TOTAL)	317 (AT 5" RES.) 846 (TOTAL)	6 (AT 10" RES.) (AND TOTAL)	---
c. DUTY CYCLE ON FLARE OR ACTIVE REGION OF AREA A (ARC MIN)^2	1	1	1/(36 A)	1
NON-FLARE OBSERVATIONS	YES WITH HIGH SENS. AND RESOLVING POWER	YES	WEAK	NO

DEFINITIONS:

FF ≡ FLARE FINDER

C MECA ≡ COARSE MULTI ELEMENT COLLIMATOR ARRAY

F MECA ≡ FINE MULTI ELEMENT COLLIMATOR ARRAY

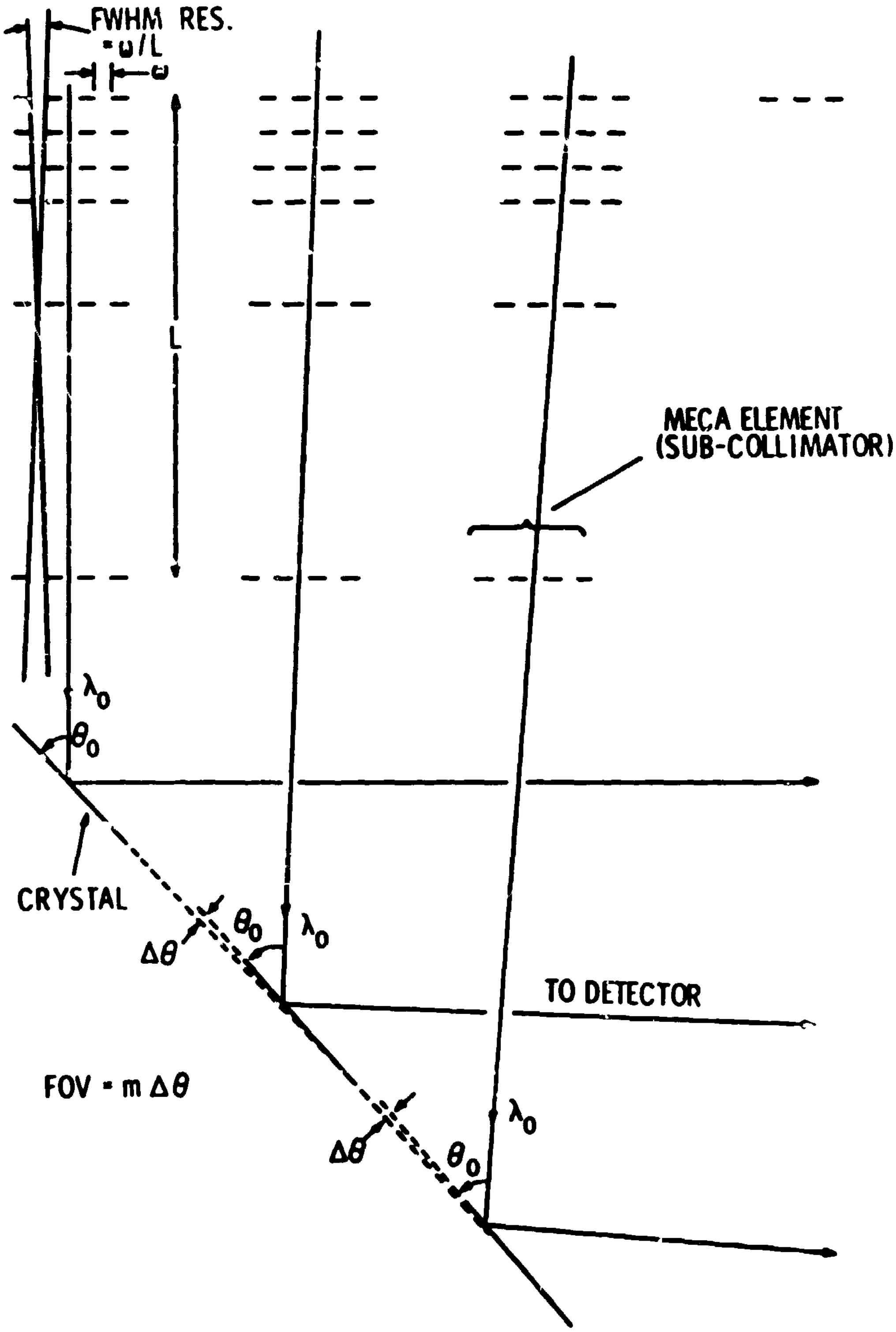


Figure 1. Multielement collimator array (MECA) concept. Collimation in one dimension is shown. Each subcollimator admits a pencil beam to its crystal and detector unit. Various subcollimator-crystal-detector units are offset from one another by Δθ to provide imaging in pixels.

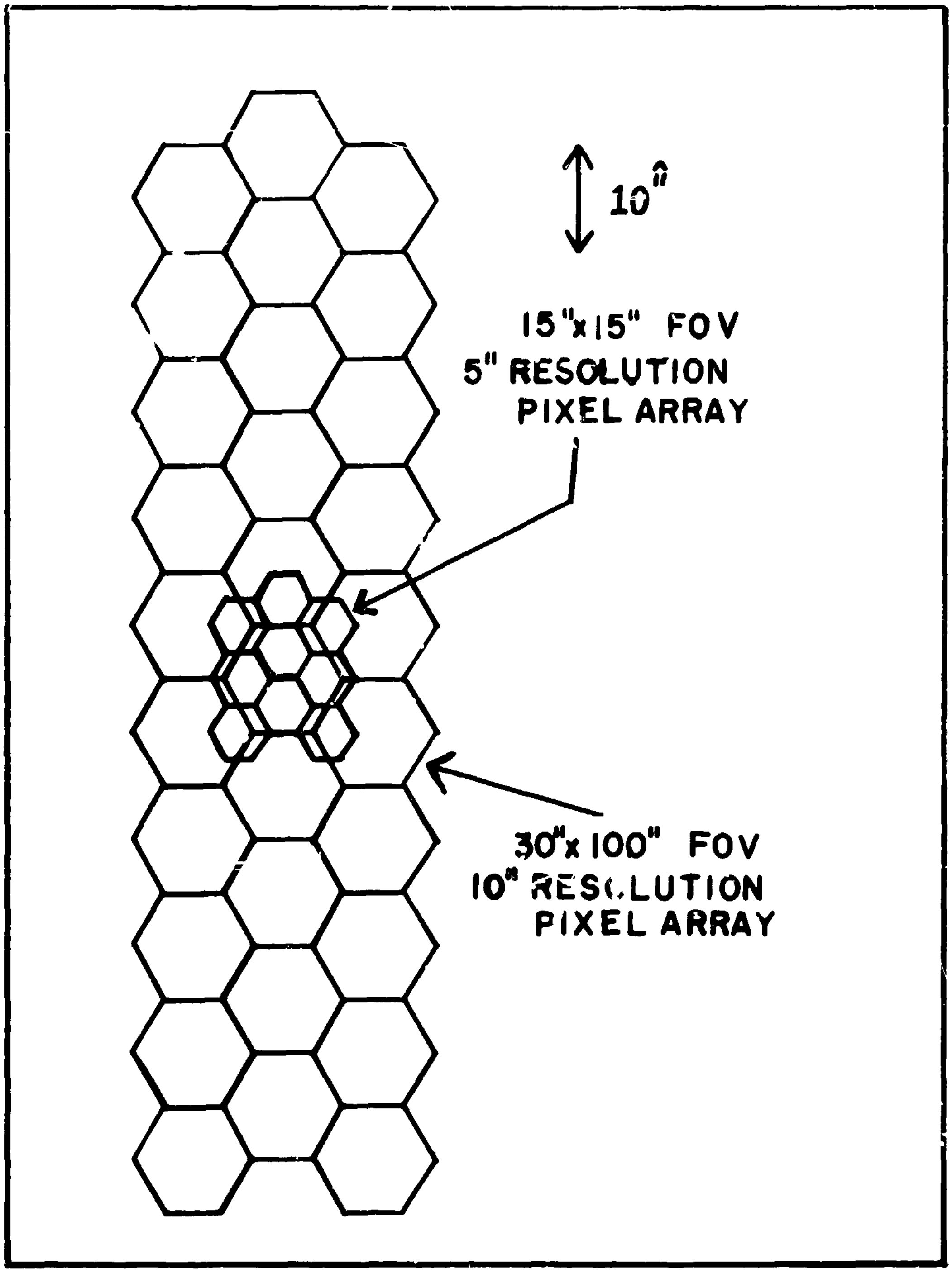


Figure 2 . The two stage nested MECA approach for the SIX experiment. Random arrays of hexagonal holes in the collimator grids form hexagonal pixels on the solar disk. Spacing of the various pixel axes, by alignment within the collimator grid frames, forms a field of view with flat spatial sensitivity.

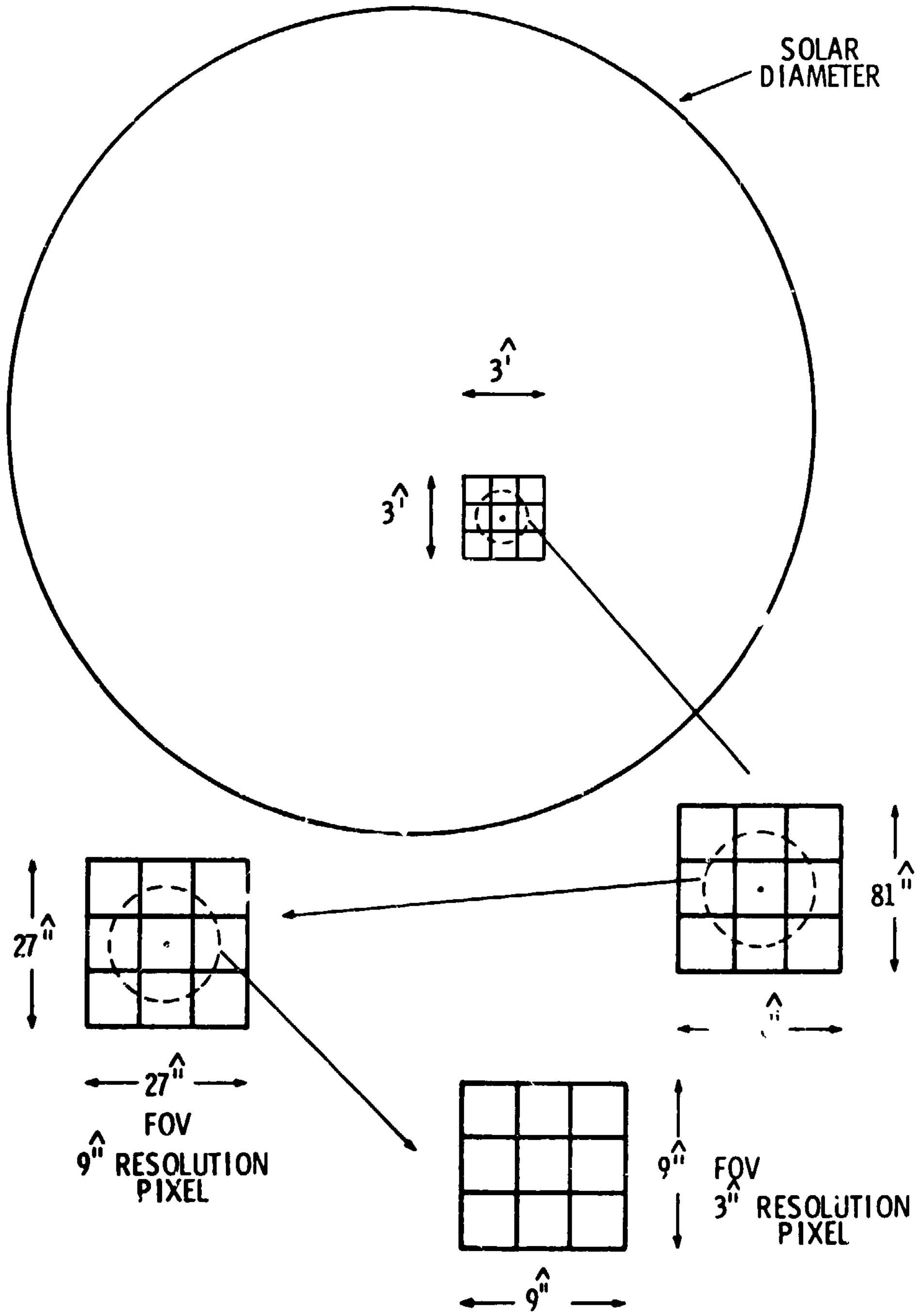
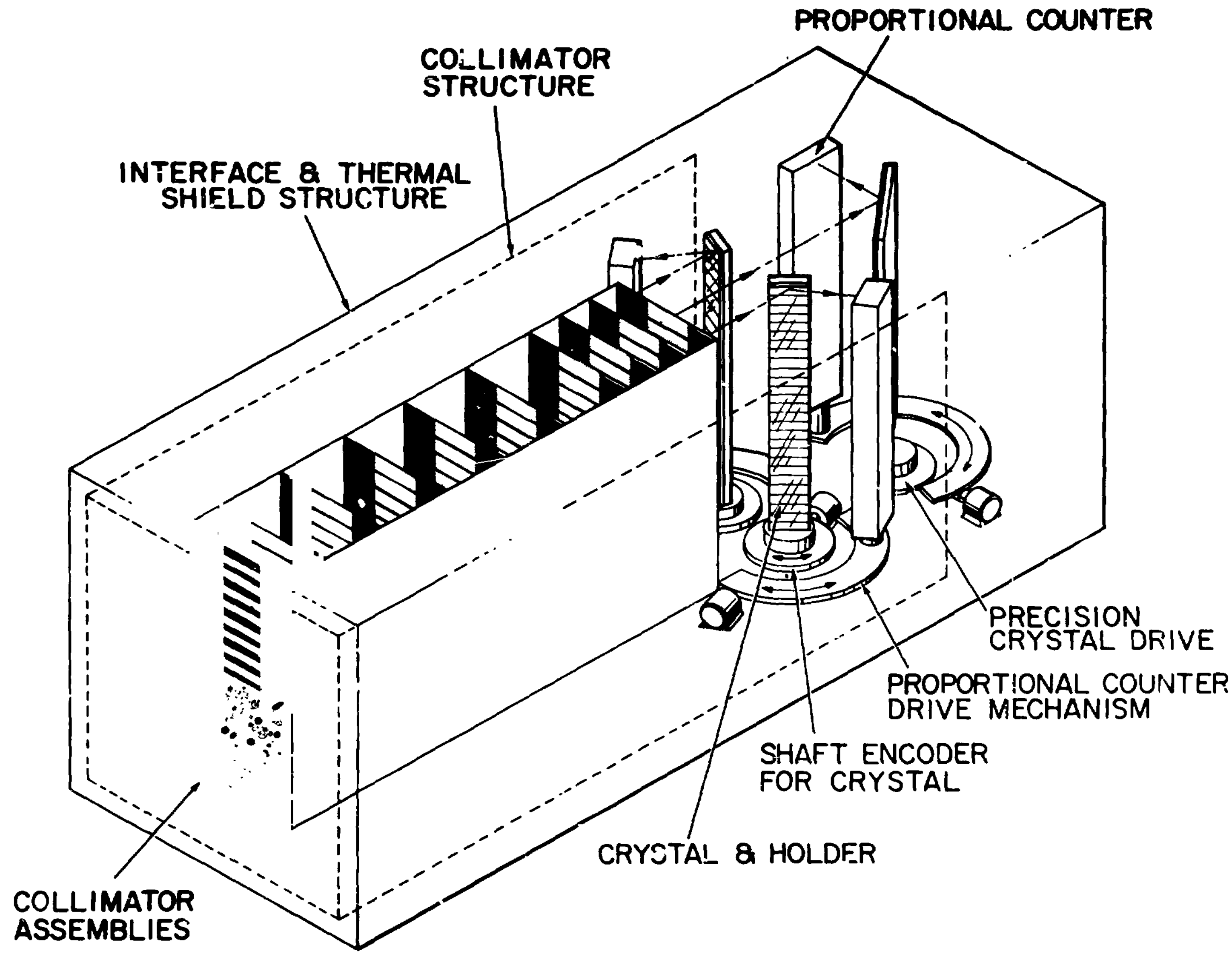


Figure 3. Imaging approach by means of nested MECA's. Nine pixels in the smallest field of view (FOV) just fill the central pixel of the next larger FOV. As the FOV increases from 9" to 180" the imaging resembles a telescope whose resolution degrades off-axis.



SPECTROMETER IMAGING XRAYS

FIG. 4

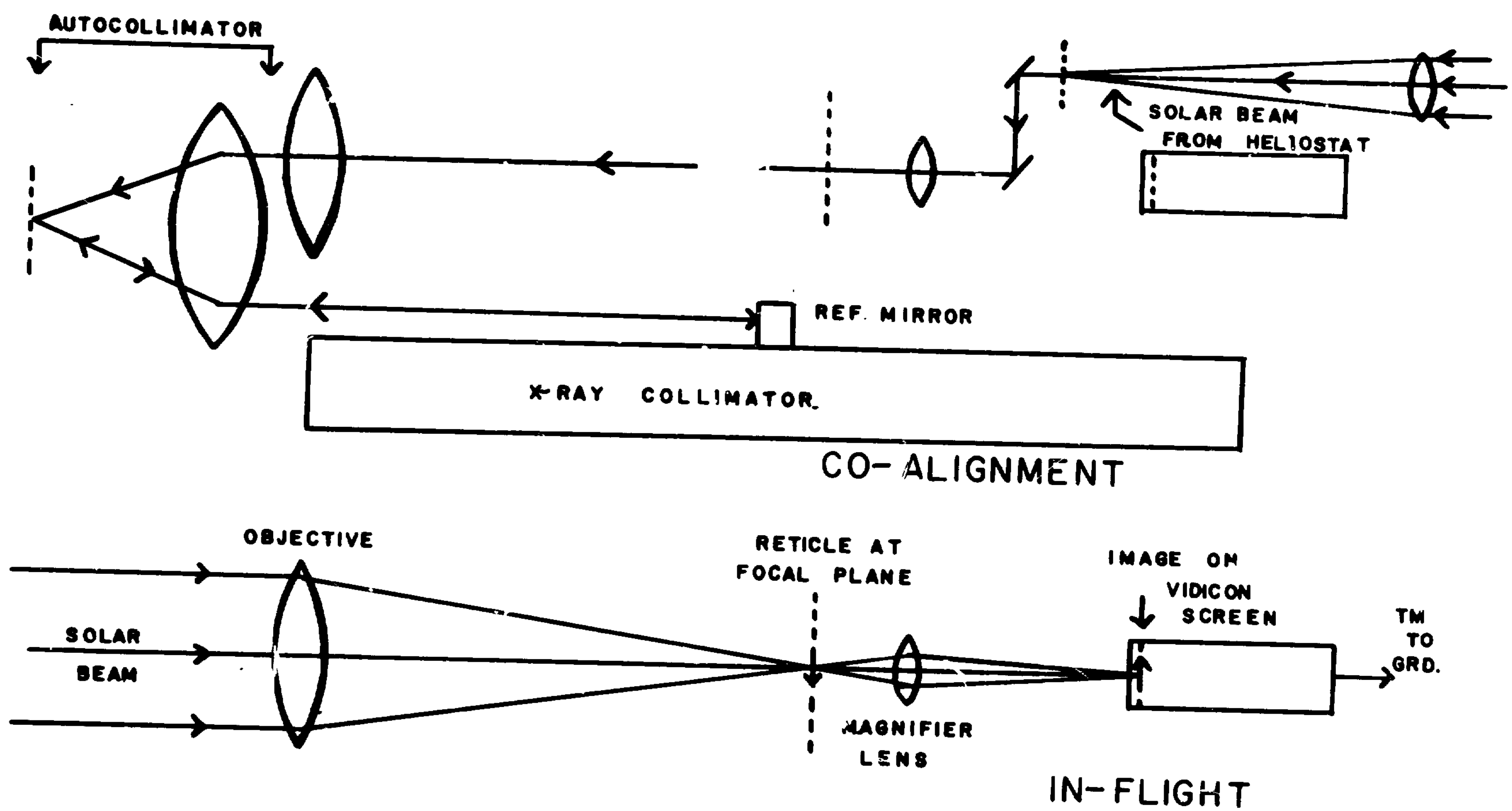


Figure 5. Rocket aspect system and co-alignment technique to be used on SIX

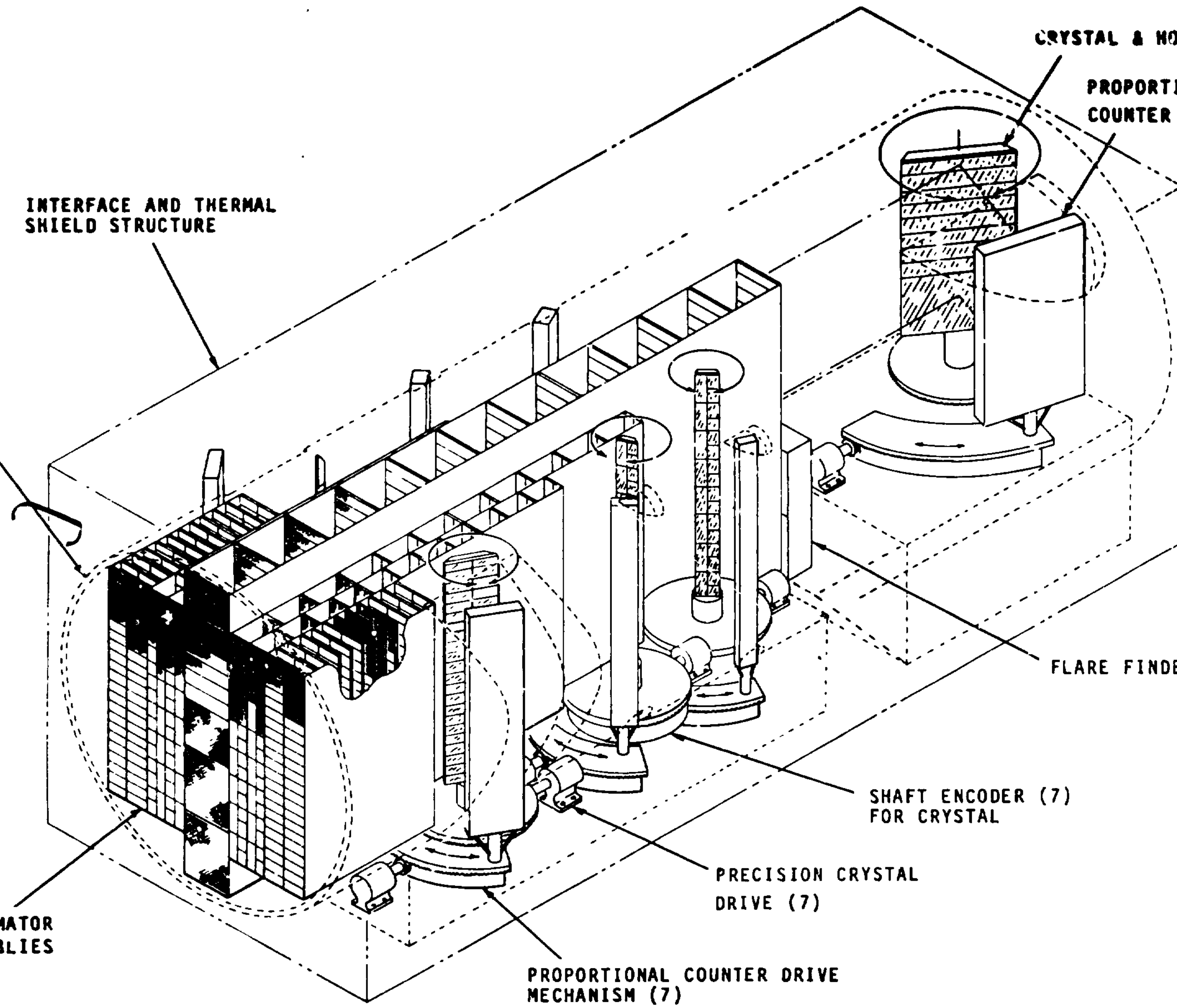


FIGURE 6. X-RAY IMAGING SPECTROMETER POLYCHROMATOR (XRISP) CONFIGURATION

N80-17963

APPLICATION OF A MAGNETOGRAPH AND X-RAY TELESCOPE TO THE STUDY OF CORONAL STRUCTURE VARIATIONS

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A very difficult problem confronting solar physics today is to determine the magnitude, structure, origin and evolution of the magnetic field, especially in the solar corona. Although excellent observations of photospheric fields are made daily, coronal fields are rarely measured, and past measurements were at very low (~ 1 arc min) resolution (Harvey, 1969). No improvement in this situation is expected soon, but powerful indirect methods of inferring facts about coronal magnetic fields exist and any program, such as SCADM, for studying the evolution of solar magnetic fields and coronal structure should utilize them. I refer to soft X-ray imaging and coronal field calculations based upon photospheric measurements. Both approaches have been used extensively, but until considerably higher time resolution and long sequences of simultaneous observations are obtained, we can hope for only incremental improvements over the results from the Skylab flight, when most soft X-ray observations were made. I will explain.

Coronal structure may conceivably evolve in three ways. Either the field lines are connected to photospheric footpoints forever and are dragged arround by convection <u>or</u> the field lines reconnect and change topology on a sub-telescopic scale <u>or</u> reconnection takes place rapidly over large volumes. We can eliminate the first possibility as being contrary to observation, even though we have never seen the reconnection process itself. The varying patterns of coronal holes and bright arcades that are so prominent in the

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*Presented at the Symposium on the Study of the Solar Cycle from Space, Wellesley, Massachusetts, 14-15 June 1979.

Skylab observations indicate that transformations between open field regions and closed field regions are common. Unfortunately, the time resolution of the Skylab observations was inadequate to reveal how an open field region becomes closed and vice versa.

Figure 1 shows one example of changes in the X-ray corona which almost certainly reflect changes in magnetic field topology, i.e., reconnection. The figure shows how two transient coronal holes grew (at 1622 UT), moved further apart (1706 UT), and faded away (2115 UT). The images are at one-orbit (~ 90 min) intervals so it is impossible to follow more precisely the evolution of these transient holes. However, by analogy with the more permanent coronal holes (Zirker, 1977), we assume that dark regions distinguish open magnetic field regions from bright, closed-field regions. Of course, X-ray brightness is determined by unknown coronal heating processes and by radiative and conductive cooling, but it seems very unlikely that these processes can suddenly go out of balance and produce transient coronal darkenings, especially in the relatively quiet region shown in Figure 1.

If coronal fields change by reconnection, how rapidly and on what scale might the process take place? The speed at which disturbances in magnetic fields propagate is near the Alfvén speed, ~500 km/sec in the corona, so we expect rapid changes -- too rapid to have been detected in the course of most observations.

Nolte et al. (1978) studied large-scale and small-scale coronal hole boundary shifts where fields are presumably opening or closing. They found that 38 percent of coronal hole boundaries shifted by more than one heliographic degree (1.22×10^4 km) per day and 11 percent of the boundaries shifted ~ 10^5 km per day. These boundary shifts are too fast to be attributed to footpoint motion and on too large a scale to be attributed to a series of sub-telescopic transformations. Nolte et al. concluded that coronal hole boundaries often, perhaps always, shift in discrete, large-scale steps, and that the changes probably reflect field reconnections. Other evidence, developed by Webb et al. (1978), links the boundary changes to transient mass ejections (Hildner, 1977) in the outer corona. The rate of these ejections is expected to vary considerably over the solar cycle, and by implication, the rate of discrete changes in the low corona should vary with phase in the cycle. It is an open question, however, of whether the dramatic differences between the sunspot-maximum phase corona and the minimum phase corona can be attributed to a succession of rapid, large-scale changes reflecting field reconnections.

If low-contrast coronal field structures reconnect at the Alfvén speed, the time resolution needed to follow the process with the resolution ($\sim 10^4$ km) provided by a practical X-ray telescope is 10 000 km ÷ 500 km/sec = 20 sec. This time resolution is achievable and it will yield new data on a fundamental physical process - reconnection - that, for many, still remains a speculation. The higher time resolution will allow us to see the discrete steps of coronal evolution clearly for the first time. At present, we know that the low corona changes by discrete steps, but observations have not had sufficient resolution in space and time to study the physical processes at work. Twenty-second time resolution and 10 arc sec spatial resolution should be sufficient for tracing structural changes taking place at the natural velocity of the magnetized coronal gas.

It has been suspected that emerging flux, i.e., relatively rapid growth of local photospheric fields, is responsible for disrupting coronal structure (Heyvaerts et al., 1977). To test this hypothesis, simultaneous photospheric magnetograms and coronal images are necessary. Substantial photospheric field changes do take place on a time scale of 10^4 sec (Rust, 1976), so magnetograms should be obtained every 10^3 sec to detect flux emergence and to follow field changes caused by supergranule flows. These changes may reveal where stresses in the low corona or chromosphere are building.

Presumably it is to relieve these stresses that reconnection and subsequent relaxation to a near vacuum field state takes place.

Field extrapolations into the corona (Levine et al., 1977) based on photospheric measurements have placed open fields in regions that later developed coronal holes. The point is not that the fields open before the corona darkens, but that the vacuum field calculations are naturally showing the lowest energy field before the corona can reach it by reconnection.

Timely sequences of magnetograms are required to probe stress build-ups (deviations from a vacuum field) by providing input to sophisticated models, which can include currents flowing in the corona. The appropriate time resolution, suggested by past observations, is 15 - 30 min, not the present standard of 24 hours. Because ground-based magnetogram sequences are always interrupted by nightfall and, frequently, by poor weather, we must place a magnetograph in space to carry out a successful coronal field investigation.

In conclusion, to study coronal magnetic fields, their daily transformation from closed to open to closed configurations, and to study how they evolve over a solar cycle, a magnetograph able to obtain uninterrupted sequences of observations over long periods should be paired with an X-ray imager of high spatial and temporal resolution on a long duration space mission or a series of short (~ 1 month) missions repeated at intervals over a solar cycle.

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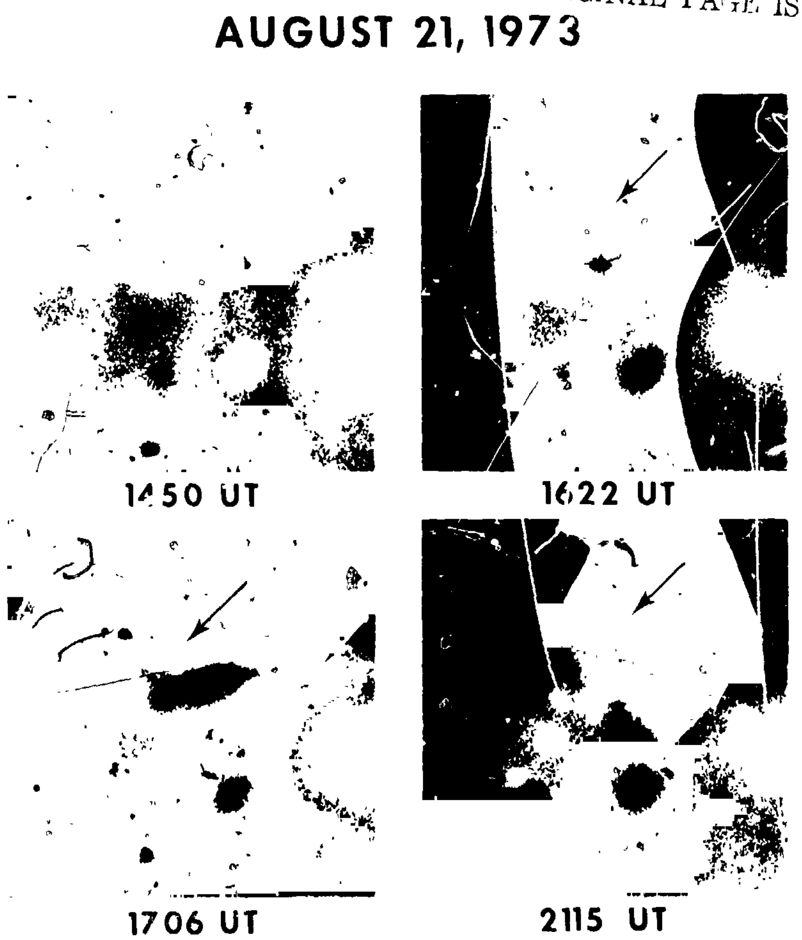

Figure 1 Evolution of transient coronal holes (arrows) on either end of a long-decay enhancement of 2 - 54 Å X-rays. Each image shows the same 6 arc min square area on the sun.

N80-17964

VARIATIONS OF THE SOLAR WIND AND SOLAR CYCLE IN THE LAST 300 YEARS

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Abstract

Because the solar wind drives geomagnetic activity and aurora, the past history of the wind and solar cycle can be inferred from records of geomagnetics and aurora. Elsewhere it was shown that the extraordinarily low level of geomagnetic disturbance around 1901 implied the solar wind velocity and southward magnetic field could not simultaneously be within the range of currently observed values. Here we show that the period about 1810 resembled the 1901 minimum and that the solar wind apparently varied in a systematic manner throughout the period from 1770 to 1857. We conclude that the solar wind and hence the sun changes on a time scale long compared to a solar cycle and short compared to the Maunder minimum and that the SCADM must include studies of this type of phenomena if it is to achieve its mission of understanding the solar cycle.

Since the central theme of the Solar Cycle and Dynamics Mission is to develop a quantitative understanding of the solar variability, the mission would best be accomplished by a combination of studies made from a satellite and other studies, both observational and analytical, which do not involve satellite observations. In this paper we give an example of the ways in which solar-terrestrial physics can contribute to SCADM objectives. We show that during the last 300 years the solar wind, and hence the sun, underwent significant variability on time scales short compared to the Maunder minimum and long compared to a single solar cycle.

The sunspot cycle from 1610-1975 is shown in figure 1, from Eddy (1976). The Maunder minimum is evident on the top line whereas the second line shows three weak solar cycles between 1800 and 1830. The third line shows a rather broad series of weak solar cycles centered on about 1900. The three periods of weak activity around 1710, 1810 and 1900 led to the hypothesis that there was an "80-100 year" cycle in sunspot activity, sometimes called the "Gleissberg cycle." Since sunspots were rare during the entire Maunder minimum, it would now be more appropriate to use the term "Gleissberg variation" to denote the three periods of weak activity near the turn of the three centuries. Here we discuss solar wind variability during these periods, with particular attention to the 1810 minimum.

The 20th century minimum has been studied by several workers using geomagnetic data as a proxy for the solar wind (Feynman, 1976, Svalgaard, 1977, Feynman and Crooker, 1978). In situ measurements of the interplanetary medium have increased the understanding of the magnetospheric response to the solar wind and permitted the development of some empirical relationships between solar wind parameters and surface geomagnetic variations. For example, the correlation coefficient between half yearly averages of midlatitude geomagnetic indices and $\langle v^2 \rangle \langle |B_Z| \rangle$ is 0.9 (Crooker et al, 1977). Here v is the solar wind speed, $|B_Z|$ is the hourly average of the component of the interplanetary field in the direction of the Earth's dipole, and <> denotes a half yearly average. A daily index of geomagnetic activity has been determined from records beginning in 1868 and extrapolation of the observed solar wind-geomagnetic relationship to earlier times can be made to estimate the condition of the solar wind around 1900. With this technique, Feynman and Crooker (1978) concluded that the geomagnetic records of 1901 were so quiet that the solar wind could not simultaneously have a speed and a $|B_z|$ within the range observed since in situ measurements began. They estimated that either the average yearly speed was less than 200 km/sec, or the southward field was a factor of three smaller than it is now, or both the speed and field were smaller than they are in the current epoch. After 1901 the level of geomagnetic activity changed so that by 1940 it was much the same as it is today.

The Maunder minimum period has been studied by Suess (1979) who used auroral and C^{14} data as proxies and concluded the solar wind was weak at that time.

In this study we utilize Rubenson's (1879) auroral frequency data from Sweden for the years 1720 to 1876 as our proxy data. Rubenson was a very careful worker and since his series was collected by a single person in a restricted area it forms as nearly a commensurate set of data as can be available from this period. When geomagnetic activity is high, aurora tend to be bright and seen relatively far south. Weak activity is associated with weak aurora occurring in a contracted oval. The total number of aurora seen in Sweden each year is shown in figure 2. In this count, if more than one observer reported the same auroral display, it was counted as a single aurora. The year is counted from June to July, but of course the catalogue shows that almost no aurora are seen in the summer months of May, June and July. Note the paucity of aurora in the years 1809-1815. In the entire period of 156 years only 14 years had fewer than 10 aurora, but of these, 6 occurred in this period of 7 years, indicating that the solar wind was in some sense weak around 1810 as it was in 1900 and at the end of the 1700's.

In order to examine this period more closely the geographic distribution of Swedish aurora is shown in figure 3. Rubenson has divided Sweden into four geographic latitude regions, from 55°N to 58°30'N, from 58°30'N to 61°30'N from 61°30'N to 65°N and from 65°N to 70°N. He reports on the number of aurora seen in each region, so that, in contrast to the count shown in figure 2, if an aurora is seen over a wide enough distribution of latitudes, it will be reported once for each district in which it is seen. In figure 3 we show the ratio of the number of aurora reported for the two most northerly districts to the number reported for the two districts south of 61°30' geographic latitude. From 1807 to 1821, i.e. approximately during the second of the three weak sunspot cycles, almost all of the aurora were seen only in the north, in agreement with the notion of a weak wind. There are two periods before 1807 and after 1821 when auroral frequency was more equally distributed between the north and the south in that aurora were seen about 1 to 3 times more frequently in the north. These two periods correspond approximately to the first and third of the three weak solar cycles. In addition there are two periods about 22 years before and after the sunspot maximum of 1816 during which the aurora were seen almost exclusively in the south. The first period of predominantly southern aurora began a year after the 1769 maximum of the sunspot cycle whereas the second period of southern activity ended a year after the minimum of 1856. The first period was 22 years long and the second 19 years.

There is, then, a period of about 90 years or 7 solar cycles during which the Swedish aurora underwent a well-defined systematic change in the pattern of occurrence, first appearing in the south, moving north and then south again.

A change in the pattern of observed occurrence of aurora can be due to several factors including a change in observers, a shift in the position of Earth's magnetic dipole, or a change in the solar wind driving the aurora. Using the Swedish data alone it appears very unlikely that a change in observers or the dipole position can be responsible for producing the pattern. There is no apparent historical reason for such a shift in observers. As far as the dipole position is concerned, during this period the dipole moved from 80°N, 307°E to 79°N, 296°E. The effect of this motion is to move a point in Sweden which is about 60° geographic latitude from about 59° geomagnetic in 1750 to 61° geomagnetic in 1850. The peak of auroral occurrence frequency in the current epoch is about 68° geomagnetic latitude in the midnight sector (c.f. Sandford, 1968, Feldstein et al, 1966). The change of about 2° in geomagnetic latitude over the century could not have caused the pattern in auroral occurrence shown in figure 3 because the dipole change was not cyclic. The pole drifted in the same direction throughout the period (Barraclough, 1974). The nonlocal nature of the pattern is confirmed by comparing the Swedish data with auroral sightings from the Boston and New Haven area (Loomis, 1866) shown in figure 4. There is a period of frequent aurora ending in 1790 and another beginning in 1839. That is, when aurora were seen predominantly in southern Sweden, they were also observed in New England. When they were seen more frequently in northern Sweden, they were not observed often in New England. When the two data sets are superimposed as in figure 5, the agreement is truly remarkable.

Since the change in the auroral occurrence pattern took place at two such widely separated locations, the cause must be in the driver of the aurora, the solar wind.

A comparison of the distribution of auroral occurrence for the IGY (1958-59) and the IQSY (1963) was made by Sandford (1968). His data show that the ratio of Swedish northern auroral occurrence to southern auroral occurrence was over twice as large for the IQSY as for the IGY. Although this is a considerable variation it is not by any means large enough to explain the variation shown in figure 3. Hence the changes in the solar wind over the

90 year period were considerably greater than the changes between the IGY and the IQSY and, since there are no recent reports of a change in auroral occurrence pattern, the changes in the 18th and 19th centuries were much larger than have been seen since in situ measurements began. There are two other remarkable observations evident in figures 3 and 4. The first is that the ratio of northern to southern aurora does not exhibit a solar cycle variation. The second is that the change in position of auroral occurrence is extremely sudden, as can be seen for 1790 and 1839 in both figures 3 and 4.

We conclude that the solar wind shows a very significant variation with the Gleissberg variation and is weak during periods of low sunspot number. The wind changes in time scales of several solar cycles and the changes are sometimes sudden. Although we have observed the solar wind for one solar cycle, we have by no means exhausted its variability.

New data on long term variability cannot, of course, be collected for our use, but a great deal of good data exists in the old literature. We need to bring new techniques of analysis to it. For example, as part of the coordinated SCADM effort we should measure the quantities that affect auroral occurrence such as the solar wind velocity, density composition and magnetic field. These observations are necessary so that SCADM studies can extract the maximum information on an important aspect of the solar cycle--its variability.

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ANNUAL MEAN SUNSPOT NUMBER, A.D. 1610 - 1975

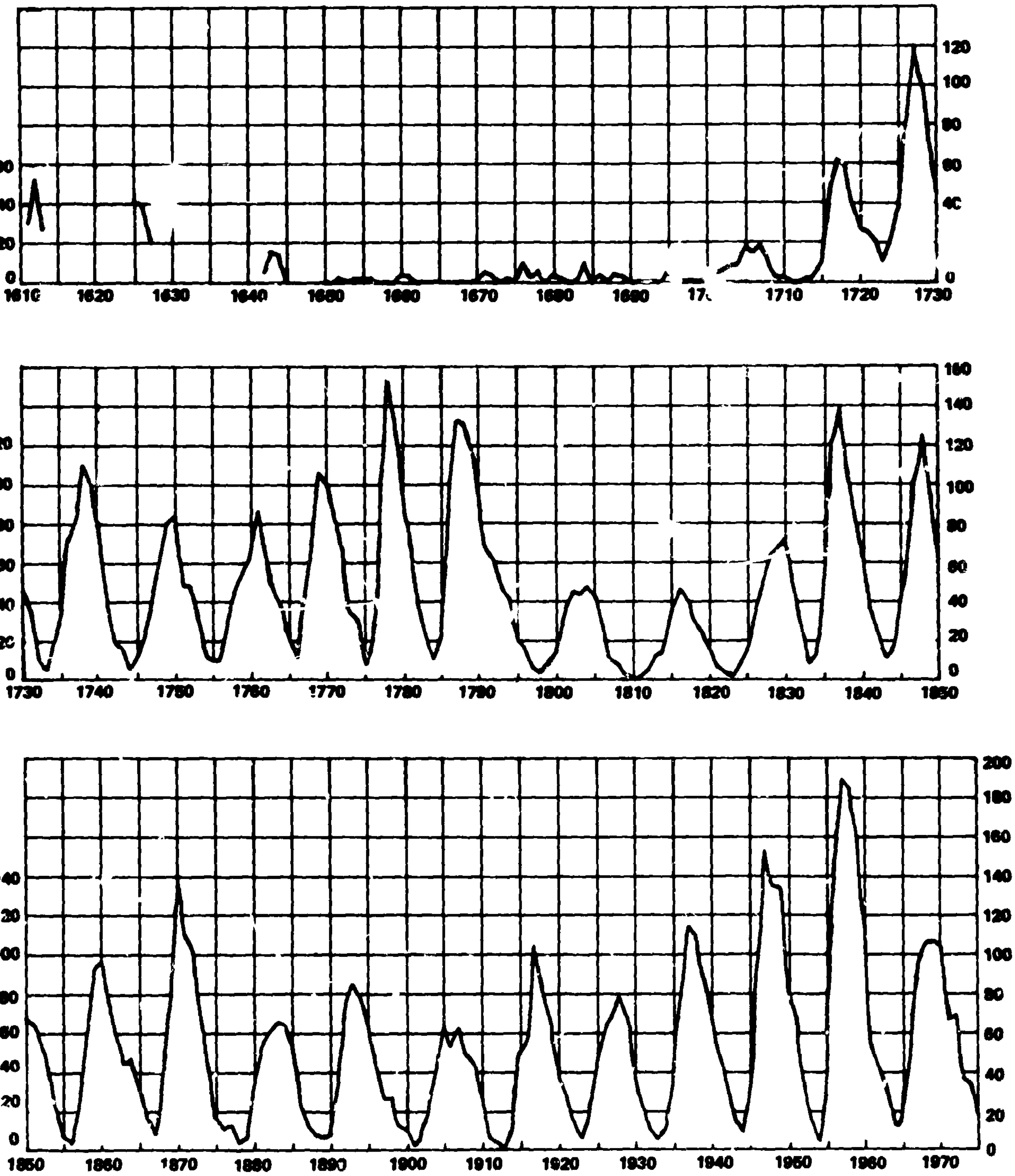

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Fig. 1. The Sunspot cycle from 1610-1975 from Eddy (1976).

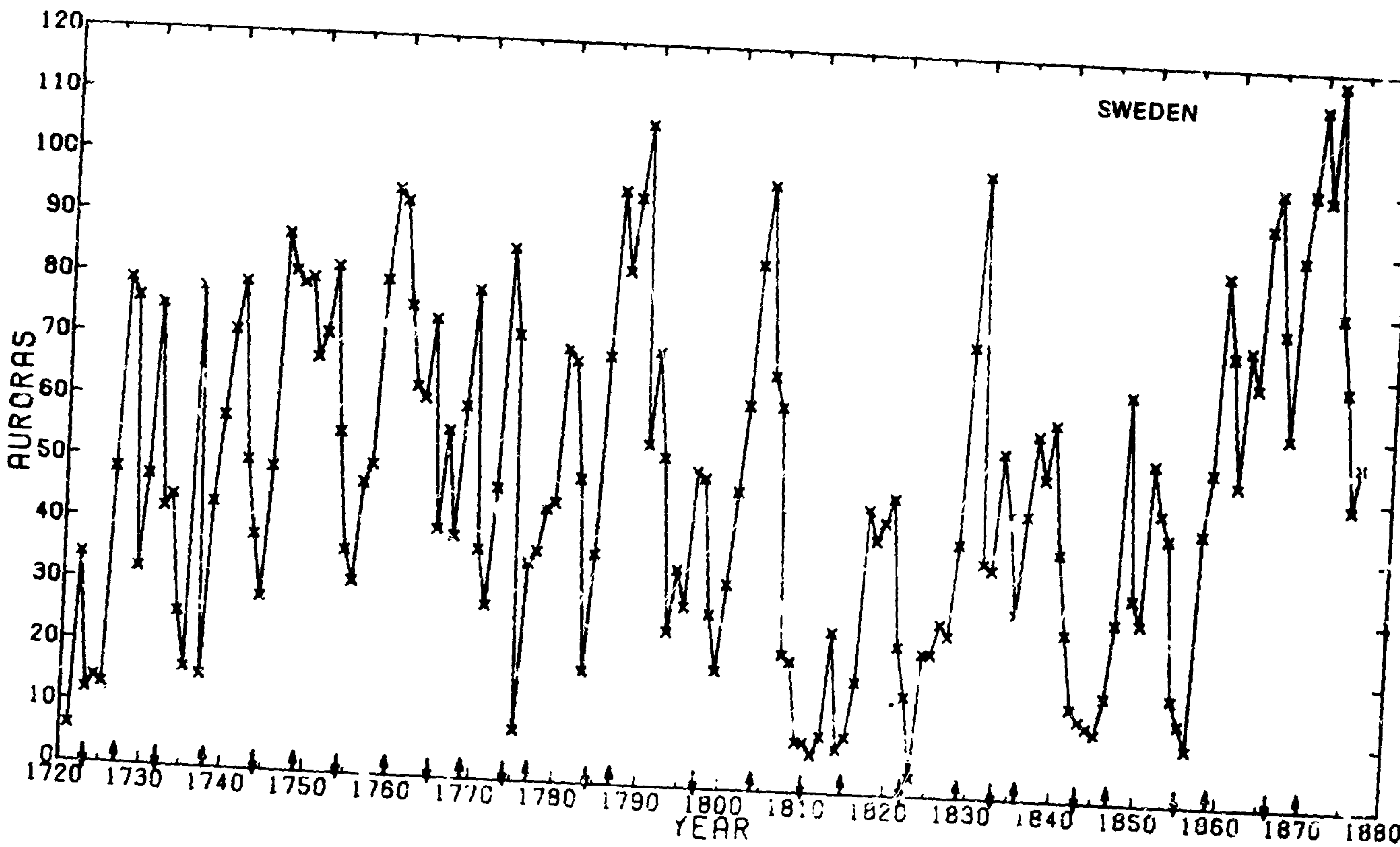

Fig. 2. The yearly number of Aurora reported for Sweden by Rubenson (1878). Note the paucity of aurora during the 6 years around 1813.

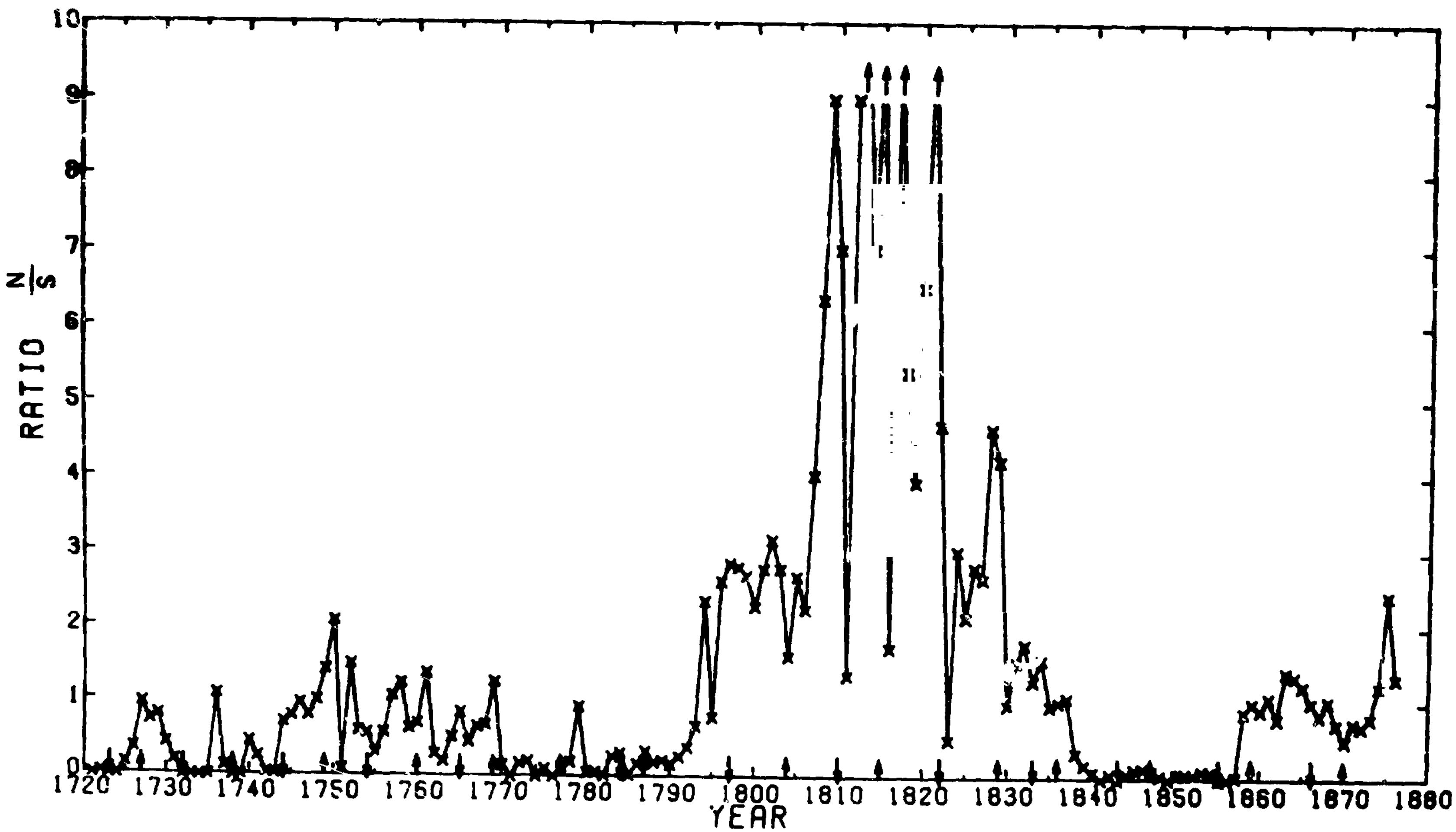

Fig. 3. The ratio of the number of aurora seen north of 61 30' geographic to the number seen south of that latitude. The data are from Rubenson (1878).

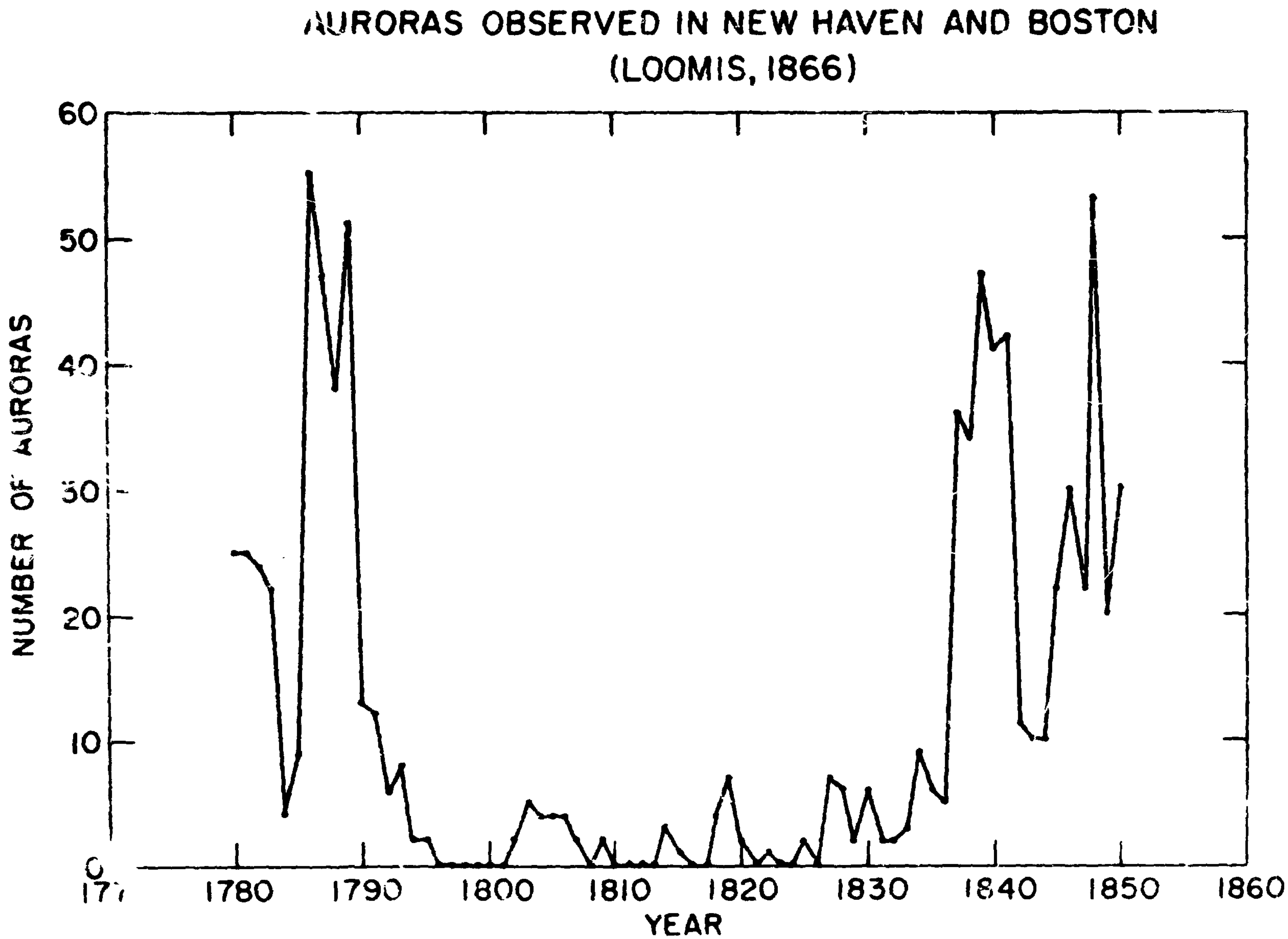

Fig. 4. The yearly number of Aurora reported from Boston and New Haven. The data are from Loomis (1866).

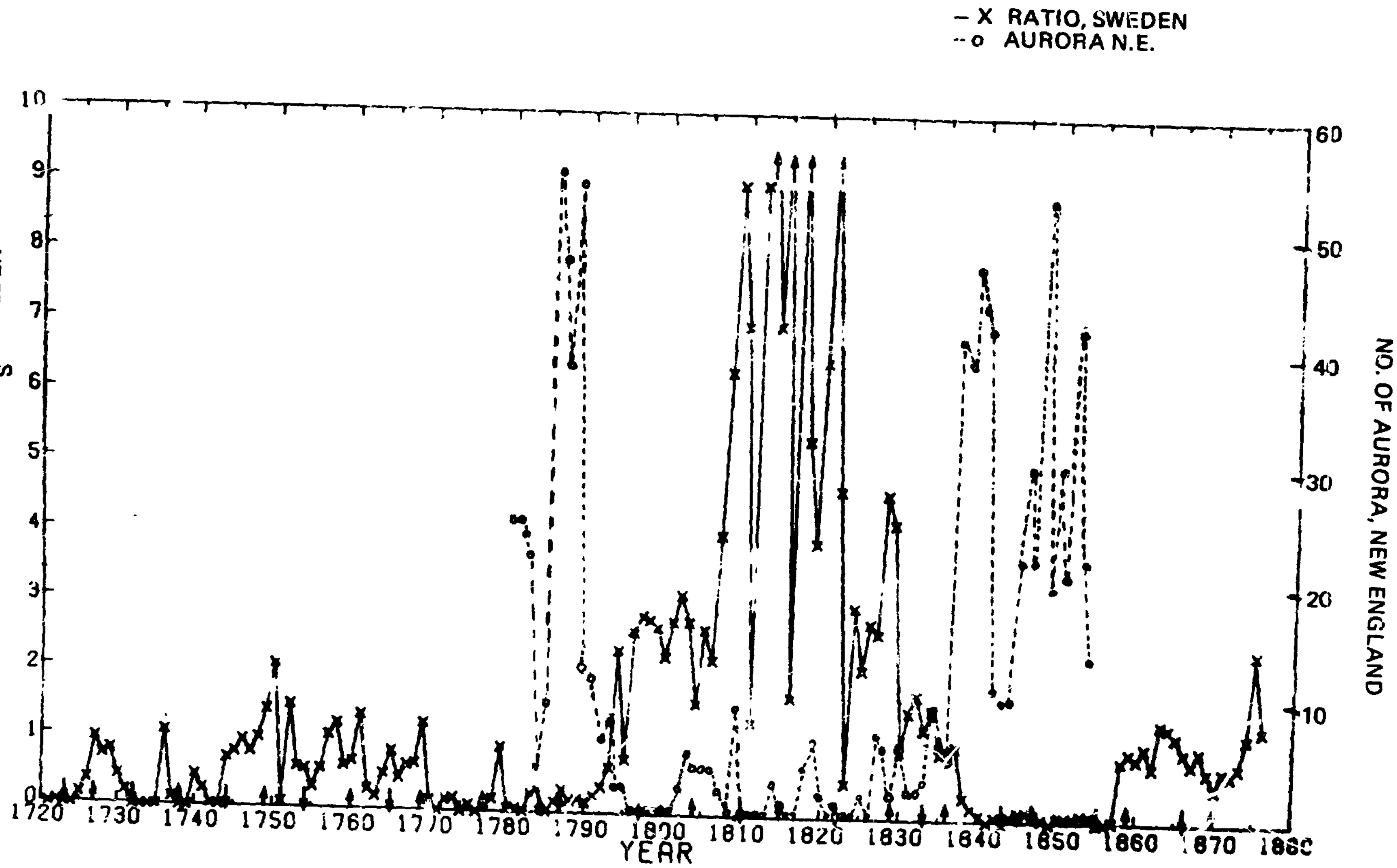

Fig. 5. A superposition of figures 3 and 4, showing that aurora disappeared from the Boston-New Haven area at the same time as they became more common in the north of Sweden. Later they reappeared in Boston-New Haven and were not seen in north Sweden.

N80-17965

Contributions of SCADM to Solar-Terrestrial Physics

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There are many different aspects to solar-terrestrial physics. Emphasis here is placed on the possible influence of variations in the solar outputs on the terrestrial climate, and the role for SCADM in such studies. SCADM should provide detailed information on variations in the solar outputs over a sizeable fraction of the solar cycle, and on the physics of the convection layer of the Sun, which is responsible for these variations. This information is essential for interpreting historical and other long-term data on the influence of solar variability on the climate, and for assessing the possible effects of short-term solar variations on the weather.

Introduction

Solar-terrestrial physics is, of course, the study of the Sun and how it influences the earth. It is a study of how various solar outputs, in radiation or particles, give rise to various terrestrial phenomena. It is a study also of how variations in the solar outputs can result in variations in the terrestrial environment, i.e., how they can produce dynamic effects in the magnetosphere, in the ionosphere, in the atmosphere, or how they can affect the climate or conceivably even the weather. Clearly, at the heart of all these transient effects, as their cause, are dynamic processes occurring in the convection layer of the Sun. Processes here can vary the solar-energy outputs which drive terrestrial phenomena. SCADM which is specifically designed to probe the physics of the convection layer, has an important role to play in studies of solar-terrestrial physics.

There are many aspects of solar-terrestrial physics that could be discussed. However, we will concentrate here on the possible influence of solar variations on the terrestrial climate which is somewhat of a controversial subject. This subject has been chosen, in part, because this aspect of solar physics distinguishes it from many other disciplines in the space program. Solar physics is at least potentially a subject of practical value in the foreseeable future.

We should perhaps ask, then, what impact new missions like SCADM can have on studies of this potentially important problem.

We will begin by reminding ourselves of some of the evidence that the Sun is variable in historical times, and that to this variability there is a climatological response. Then we will discuss briefly how SCADM can play an important role in studies of these phenomena.

Solar Variability

It has been well known for more than 100 years that the Sun has an approximately 11-year cycle in activity, as is measured by sunspots (Schwabe, 1843). However, it has only recently been called to the attention of modern solar physicists, principally through the pioneering work of Jack Eddy, that the solar activity cycle is neither constant in amplitude nor in duration, and perhaps most important, that in historical times there have been periods when the activity is essentially absent.

Shown in Figure 1 is a plot of the annual mean sunspot numbers from 1610 to the present, which is taken from a recent review article by Eddy (1977a). Accurate sunspot records were kept starting in about 1850. The remaining parts of the curve are determined from historical records that were assembled shortly after the cycle's discovery. As can be seen in the figure, there is perhaps a general envelope to amplitudes of the cycles of eighty or ninety years in duration. It can also be seen that there was a period from about 1645 to 1715, the so-called Maunder minimum, when solar activity as measured by sunspots was essentially absent.

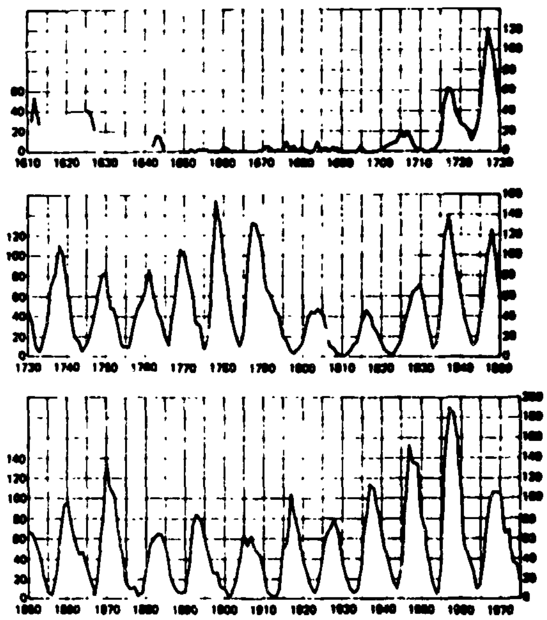

Figure 1. The annual mean sunspot numbers (from Eddy, 1977a).

A skeptic could argue that sunspot measurements were sufficiently unreliable in the 1600's, so that the existence of the Maunder minimum is not statistically significant. However, the corroborating evidence to the sunspot record, which Eddy has assembled, is impressive. Aurora, which are well correlated with solar activity, were reported less frequently during the Maunder minimum. First-hand descriptions of solar eclipses during the Maunder minimum show no evidence for a pronounced solar corona, as might be expected in the presence of reasonable solar activity (Eddy, 1977a). The existence of the Maunder minimum is beyond question.

If we want to extend our information on solar activity to still earlier times, we of course have an immediate problem. The telescope was only discovered in about 1610, and so before this time only naked-eye sightings of sunspots are available. Such sightings, however, are too random to be of much significance. Similarly aurora or eclipse sightings are too infrequent and too subject to sociological factors to be of much use. Thus, for measurements of the past behavior of the Sun, we have to rely on various proxy measurements of solar activity, the most common of which comes from ^{14}C studies.

Medium-energy galactic cosmic rays, which impinge on the upper atmosphere of the earth, produce ^{14}C which eventually finds its way to plants, where it is assimilated and absorbed. The cosmic-ray flux, in turn, is inversely correlated with solar activity: during periods of high solar activity, e.g., solar maximum conditions, the cosmic-ray flux is low. Thus, the ^{14}C abundance in the atmosphere should also vary inversely with solar activity, or equivalently the ^{14}C content in, for example, tree rings can be used as a measure of the long-term history of solar activity.

The plot in Figure 2, which is a portion of a figure presented by Eddy (1977b), summarizes the long-term variations in the ^{14}C content in tree rings, relative to a standard reference value, over a 7000-year period. The ^{14}C is shown with increasing content plotted downward; ^{14}C varies inversely with solar activity, so a high plot here implies high solar activity. We note that first-order changes in ^{14}C which are due to variations in the earth's magnetic field

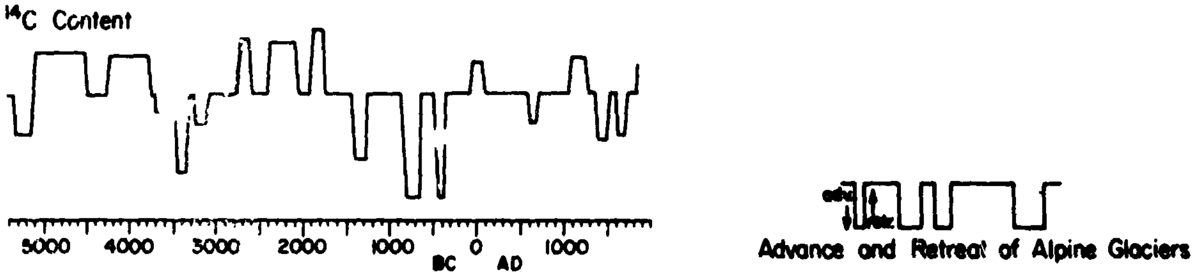

Figure 2. Long-term deviations in ^{14}C; downward excursions refer to increased relative ^{14}C and imply decreased solar activity. Also shown are times of advance and retreat of Alpine glaciers (from Eddy, 1977b).

have been removed from this plot. The ^{14}C changes shown in Figure 2 are believed to be due primarily to solar activity changes.

We cannot use the ^{14}C measurements to tell us about fine details like the solar cycle. The atmosphere tends to act as a low-pass filter which is insensitive to changes in ^{14}C production on scales less than about 20 years. However, we can use these measurements to infer overall trends in solar activity. We can see, for example, the effect of the Maunder minimum in the 1600's. Moreover, we can infer that this period of low activity was not an isolated event. Rather there have been other periods of low activity, e.g., in the 1500's, which is the so-called Spörer minimum, and at other times back into antiquity. Conversely, there have been periods when solar activity was enhanced over its present level, such as in the 12th century (Eddy, 1977b).

It is interesting to note also that if we assume a linear relationship between the ^{14}C and solar activity, which is perhaps unwise, the dynamic range of solar activity implied by this plot is quite large, and greatly exceeds the range of solar activity that we have observed since the advent of regular sunspot measurements in the 1850's. Our current observations, then, have exposed us to only a small segment of the Sun's full repertoire.

Another fascinating example of a possible variability in the Sun was reported at the recent AAS meeting at Wellesley by Jack Eddy, who argued that the Sun appears to be shrinking. By studying the measurements of the diameter of the Sun, which were made by the Greenwich Observatory and the Naval Observatory in Washington, D. C. over an approximately 150-year period, Eddy finds that the solar diameter appears to decrease systematically with time at a rate of about 0.1% per century (Eddy, private communication, 1979). We can be concerned, of course, that this effect is not real, but rather is caused by, for example, a deterioration in atmospheric seeing conditions over this time period. As a counter argument, Eddy notes that the deterioration in seeing conditions that is needed to explain this observation is quite large. Moreover, there was an eclipse in 1567 which, with the current diameter of the Sun, should have been total, but in fact was observed to be annular, indicating that the Sun was slightly larger in the past.

There are also some other curious variations in solar conditions on similar but somewhat smaller time scales. In a recent paper Feynman and Crooker (1978) point out that geomagnetic activity is caused by the solar wind, and thus we can use indices of geomagnetic activity, which have been recorded for most of this century, to tell us about the recent history of the solar wind.

Shown in Figure 3 is a plot of the so-called *aa* index of geomagnetic activity, which has been accurately and stably measured since about 1900 (Feynman and Crooker, 1978). We note that, in addition to an 11-year variation, the *aa* index has been essentially systematically increasing since that time. Crooker *et al.* (1977), in an earlier work, showed that for the last solar cycle, where there are good spacecraft measurements, the *aa* index is roughly proportional to the product of the southward component of the interplanetary magnetic field and the solar wind speed squared. Presumably, this result can be interpreted physically as being due to the V×B electric field in the solar wind being convected past earth at the solar wind speed. If we assume that this relationship also held back in 1900, we can use it to estimate the solar wind speed and magnetic field at this time. We find, of course, that either the solar wind speed and/or the southern component of the magnetic field must have been substantially smaller back in 1900. For example, if the field strength was the same then as now, the solar wind speed would have to have been roughly a factor of two smaller in 1900, or an average speed of less than 200 km/sec. Thus a substantial change in the solar wind over an 80-year period is indicated.

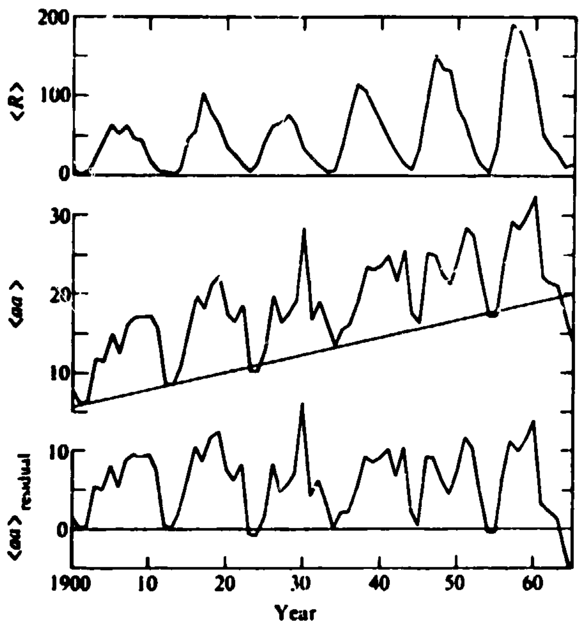

Figure 3
Yearly means of sunspot number, the *aa* index, and residual *aa* which is obtained by subtracting the long-term trend in *aa* from the measured value (from Feynman and Crooker, 1978).

We have evidence, then, that the Sun varies over time scales of centuries. This result is of course an interesting scientific problem in its own right. However, it may also be a problem with practical consequences. In view of the fact that the earth's climate is obviously dependent on the Sun, it might not be unreasonable to expect that there is some terrestrial response to this solar variability. In fact there is some evidence which suggests that this is the case.

Possible Climatological Responses

It is well known that during the Maunder minimum the climate in northern Europe was unusually cold; in fact it exhibited the coldest excursion of the so-called Little Ice Age (Eddy, 1977b). Moreover, if we plot the advance and recession of

Alpine glaciers in northern Europe, which is also shown in Figure 2, we find a striking correlation. During periods of low solar activity, such as in the Maunder minimum or the Spörer minimum, the glaciers grow, indicating a colder-than-average climate. During period of high activity, such as in the 1200's, the glaciers shrink, indicating a warming trend. In fact the period in the 1200's is known as the Medieval Climatic Optimum (Eddy, 1977b).

These records of climate changes in northern Europe are of course not in themselves an indication of worldwide climate changes. However, even if solar variability results in major climate changes only in isolated regions, e.g., only in northern latitudes, it is still an effect of major importance.

There is also evidence of correlations between changes in the Sun and changes in the climate on shorter-time scales than centuries. The best established correlation is probably the 22-year drought cycle in the western United States. In the Goddard symposium in 1975 Roberts (1975) reviewed work that showed that there is a marked tendency for droughts in the High Plains region, over the past century and a half, to occur at a 20- to 22-year interval, in phase with the double sunspot cycle; and thus presumably in phase with the magnetic cycle of the Sun. More recently Mitchell *et al.* (1979) have used tree-ring data to define an annual drought index for the central and western United States. Again they find that these droughts tend to occur in every other solar minimum.

On shorter-time scales still, the correlations between solar variations and terrestrial climate, or even weather phenomena, get more confused. The literature is filled with various claims for correlations, some of which hold for a time and then disappear, or even become an anticorrelation. This difficulty in determining short-term correlations is of course not surprising. The atmosphere is a complicated system with its own internal variations and responses, and discerning the signal of a solar-induced variation, which may be weak, from strong atmospheric noise, particularly from measurements in isolated regions, is a tricky business. Indeed, the mere fact that the effect is hard to find should make us skeptical that on these short-time scales it is important. We should remain doubtful that solar variability is ever going to contribute to the six-o'clock forecast.

One short-term measurement, however, that has been claimed to be correlated with solar phenomena is the vorticity area index, which is a measure of the area at the 300 mb range in the atmosphere, where the vorticity exceeds certain levels. It is basically a measure of the storminess and precipitation in low-pressure troughs (Herman and Goldberg, 1978).

Wilcox *et al.* (1973a,b; 1974), following earlier work by Roberts and Olson (1973), plot the total vorticity area index for the northern hemisphere (north of 20° N) versus sector boundary crossings, as is shown in Figure 4. In the top panel the data are divided into those sector crossings in which the interplanetary field changes from positive to negative polarity, and from negative to positive; the second panel is for the first and second half of the various winters (the correlation exists only for the winter months); and the bottom panel is for the years from 1964-66, and from '67-'70. The response in each panel is similar. The vorticity area index starts decreasing before the arrival of the sector boundary and decreases for several days thereafter.

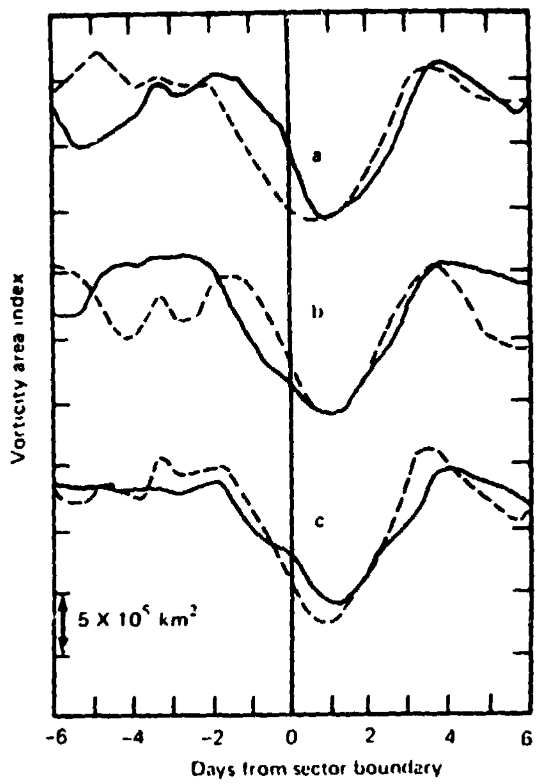

Figure 4
Average response of vorticity area index for magnetic sector boundary passage on day 0. Curve a: dashed, 30 boundaries separating positive-to-negative sectors; full, 24 boundaries separating negative-to-positive sectors. Curve b: dashed, 22 boundaries in second half of winter; full, 32 boundaries in first half of winter. Curve c: dashed, 28 boundaries in the interval 1967-1970; full, 26 boundaries in the interval 1964-1966. Total of 54 boundaries. Ordinate axis in units of $5(10^5)$ km^2. From Wilcox *et al.* (1973a).

We should not conclude that sector boundaries are necessarily the cause of the effect shown in Figure 4, since clearly the effect sets in before the arrival of the sector boundary. Rather, sector boundaries can be correlated with other solar outputs, such as solar wind or energetic particles, which may be the cause. Moreover, as an indication of the confusion which exists with short-term responses like this, Williams and Gerety (1978), in a recent paper argued that the correlation shown in Figure 4 disappeared in 1974-77. This result is somewhat disturbing since during this time interval the sector structure was better defined than in almost any other recent period (Hundhausen, private communication, 1979).

We know, then, that the Sun exhibits variations. There are the well-known 11- and 22-year cycles, and there is evidence that there are major long-term changes in the level of solar activity, on the scale of centuries. There is evidence, too, which suggests that there is a terrestrial response to this solar variability. Climate changes occur at least in certain regions concurrent with the long-term variability. There are 22-year drought cycles, and perhaps, although the situation is more confusing, some shorter-term response. We should be careful, however, not to overstate the case. The evidence suggests that something is happening. But what actually is happening, and how it works, is beyond our current understanding. However, the suggestion of a cause-and-effect relationship between solar variability and at least the climate is sufficiently strong, and the implications of this problem sufficiently important, to warrant serious scientific attention.

The Role of SCADM

There are two basic approaches that can be taken to this problem. We can recognize that for the long-term variations, e.g., on the scale of the Maunder-minimum or even for the 22-year drought cycle, the signal of a solar terrestrial relationship is likely to be the strongest. Short-term internal variations in the atmosphere should average out on these scales and may reveal the solar signal. The approach here, then, would be to probe more deeply into the historical data or other measures and attempt to understand exactly how the earth's climate has been influenced by solar variations in the past. The difficulty with this approach, of course, is that knowledge of the past behavior of the Sun is only through various proxy indices, such as sunspots, or cosmic rays as measured by ^{14}C. No one argues, of course, that sunspots themselves influence the climate. Rather changes in the sunspot cycle must indicate that there is some change in some part of the solar outputs, and this influences the climate. But how sunspot activity is related to variations in the solar outputs is presently unknown. The same conclusion holds for the cosmic rays. There are mechanisms which use cosmic rays to influence the weather or the climate. However, in this context changes in the cosmic rays as seen in the ^{14}C are a measure of changes in the solar magnetic field and thus the heliospheric field, or in the solar wind. But what these changes are, no one knows. It is a disturbing fact that despite several decades of study we do not know what changes in the cosmic-ray flux imply about changes in solar or heliospheric conditions. We do not know what causes the solar modulation of galactic cosmic rays (Fisk, 1979).

An alternative approach is to look for a coupling between solar variability and the climate or the weather on short-time scales. Here, we can in principle make very detailed measurements, and we can attempt to identify and study actual physical processes which are responsible for the coupling. Again, the effect may not be important for short-term weather phenomena. However, if we understand how it works on the short-time scales, we may be able to understand how it works on long times, where it can be important. But of course if the solar-induced effect is not important for the atmosphere on the short-time scales, if it is small in comparison with the natural, internal variability in the atmosphere, it will be difficult to observe.

For both of these approaches, however, essential information, in fact one of the more promising directions in which to proceed, is to concentrate on understanding what in fact the Sun is doing, and how it works. If we had even a clue as to what changes in the sunspot cycle imply about changes in solar output, or how cosmic-ray modulation works, our ability to interpret and to understand the historical data would increase immeasurably. A similar conclusion holds for the short-term studies. The atmosphere is complicated and its behavior is confusing and driven by physical processes unrelated to solar variations. The more promising approach for solar climate or weather studies is to determine first and in detail what in the solar outputs is varying. Then we can concentrate our search for a response, which we can study, in appropriate regions of the atmosphere. And we are in need here not of proxy indices like sector boundaries, but of actual detailed measurements of solar outputs in radiation and particles.

Let us be somewhat more specific here. The first question that one should ask in studies of whether variations on the Sun influence the climate is: 'Is the solar constant constant?' A principal criticism against the claim that variations on the Sun can influence the climate or the weather is that the energy involved in the obviously variable components of solar radiation, such as the UV flux, is exceedingly small. However, if there is a variation in the solar constant, the energetics problem disappears.

It is important to realize here that the climate is very sensitive to the solar constant. For example, the current theory for major periods of advance and retreat of glaciation is that an interplay between changes in the orbital parameters of the earth results in changes in the amount of solar radiation that is received as a function of latitude and season (e.g., Milankovitch, 1930, 1938).

The maximum change in the total solar radiation received at a given location due to this effect, which results in major glaciation, is only a few %. Changes of less than this, by say less than 1% in the solar constant, are expected to produce climate changes similar to those that occurred at the Maunder minimum. In fact current climate models indicate that changes in the solar constant by as little as 0.1%, provided that they occur over a sufficiently long time period, can result in climate changes of economic importance.

Clearly, we are in need of determining with high accuracy whether the solar constant varies, and we are in need of making these measurements over at least some sizeable portion of a solar cycle. Measurements of variations in the solar constant would have several implications: It would provide us with a straightforward means by which variations in the Sun could influence the earth. Second, if we saw short-term variations in the solar constant, over the scale of the solar cycle, we would be more inclined to believe that long-term changes are also possible, and that this would be the probable cause for the long-term climate changes on the scale of centuries. And third, and perhaps most important, if we were able to observe how any changes in the solar constant are related to other changes on the Sun, such as to changes in sunspots or coronal holes or to fluid patterns in the convection layer, we may develop an understanding of possible causes of the solar constant changes, and perhaps a means for estimating likely changes in the solar constant in the past or even into the future.

There is in fact some evidence that the solar constant does vary. In a recent issue of Geophysical Research Letters, Kosters and Murcray (1979) report that the solar constant that they measured in 1978 is 0.4% larger than what they measured with the same instrument in 1968, and that this change is significantly larger than the expected experimental uncertainty. However, Hoyt (1979) has argued recently that the Smithsonian Astrophysical Observatory ground-based observations of the solar constant show no change to within 0.1% from 1923-1954, and that changes no larger than a few tenths of a percent are observed from 1902-1962.

SCADM, with its capability of measuring the solar output continuously and, more important, with its capability of relating any changes in the solar constant to the behavior of the convection layer of the Sun, and thus to the physics of the convection layer, is an ideal mission to pursue these studies.

If the solar constant is constant, or for that matter even if it isn't, we have to be aware that the coupling between changes on the Sun and changes at the earth could be by some subtler means. Some component of the solar output with little energy may still be able to produce a major effect.

The ideas here generally fall in two categories: First, it may be that the solar variation only produces a small effect in the atmosphere, but that this effect is amplified by some other means. For example, some portion of the solar outputs, e.g., solar energetic particles, can reduce the ozone layer, and this causes lower temperatures in the stratosphere and more UV flux and higher temperatures at lower layers (Zerefos and Cruntzen, 1975). It may also be that some part of the solar outputs has little energy content, but that this energy is dumped in some part of the atmosphere where it is not insignificant. For example, in a geomagnetic storm, energy which is stored in the geomagnetic tail is dumped, through energetic particles, into the upper atmosphere. This dumping occurs only in a narrow latitude range, circumvolving the poles, where the magnetic field lines from the geomagnetic tail connect to the earth. In the northern hemisphere in the winter, where the solar radiation is reduced, because the earth is tilted away from the Sun, and because the albedo may be increased with more snow and ice on the ground, this energy in precipitating particles can be a sizeable fraction of the total energy in solar radiation, and conceivably may have an effect on the atmosphere (Herman and Goldberg, 1978). It is interesting to note, for example, that the correlation between sector boundary crossings and the vorticity area index at northern latitudes only occurs in the winter months (Wilcox *et al.*, 1973a,b, 1974).

None of these possible mechanisms has been established to be important; they are only ideas. However, SCADM, with its capability of measuring the radiation output of the Sun in detail, as a function of wavelength, can make an important contribution to these studies. We should recognize that in the time period when SCADM is to fly, we also hope to have the OPEN mission underway, with four spacecraft studying solar particle output, and energy-transfer processes in the earth's magnetosphere. UARS may be making atmospheric measurements. Solar Polar will be studying the heliosphere in three dimensions. We may have a unique opportunity, in the late 1980's, to learn how the outputs from the Sun vary, how the heliosphere varies, and how the terrestrial environment responds.

However, the most important role of SCADM must be to probe the physics of how it all works. The underlying causes of all solar terrestrial variations are the dynamic processes occurring in the convection layer of the Sun. It is this that we must attempt, through missions like SCADM, to understand. We are in many ways like the geophysicists in the pre plate Tetonic era. Until we have some understanding of the underlying physics which governs the variations that we see, we cannot hope to put the pieces of the various puzzles together. We cannot hope to make some sense out of solar variability as an interesting scientific , and sense out of the terrestrial response to this variability, as a subj t of potential practical value.

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QUESTIONS AND COMMENTS

COMMENT BY: S. T. Seuss, NOAA/ERL/SEL

DIRECTED TO: L.A. Fisk

In the prepared summary on the contribution of SCADM to solar-terrestrial physics, Len Fisk placed his emphasis on sun-weather/climate relations. Another important contribution would be to the service-oriented science. There are large numbers of users of solar-terrestrial data who depend on daily, or even hourly updated and forecast information on geomagnetic activity, the ionosphere, magnetosphere, solar activity, UV/EUV solar irradiance, solar X-rays, and so on. The forecasts of larger scope, up to and including sunspot number for years in advance are also in great demand. These services depend on a comprehensive empirical description of the relationship between parameters observable from the ground and the many parameters observable only from space. Such an empirical description can only be supplied by a mission like SCADM, lasting over at least a major portion of a sunspot cycle. The return could be measured in terms of service and cost benefits and should not be relegated to a subsidiary importance in comparison to more spectacular but less beneficial scientific objectives.

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CONTROL OF THE EARTH'S ELECTRIC FIELD INTENSITY THROUGH SOLAR WIND MODULATION OF GALACTIC COSMIC RADIATION: SUPPORT FOR A PROPOSED ATMOSPHERIC ELECTRICAL SUN-WEATHER MECHANISM

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Summary

The ionospheric potential and galactic cosmic radiation have been found to be inversely correlated with the solar wind velocity. Since the ionospheric potential is proportional to the fair-weather electric field intensity and cosmic radiation is the dominant source of atmospheric ionization, these findings indicate that the earth's overall electric field varies in phase with atmospheric ionization and that the latter is modulated by the solar wind. These findings are in agreement with a proposed mechanism in which solar control of ionizing radiation influences atmospheric electrification and thus possibly cloud physical processes. The latter would affect atmospheric energetics. An experimental approach to critically test the proposed mechanism through comparison of the temporal variation of the earth's electric field with conditions in the interplanetary medium is outlined.

Background

In recent years there has been rapidly increasing interest in the possibility that variable solar activity may affect weather and climate. A decade ago consideration of the configuration of the interplanetary magnetic field (IMF) relative to sun-weather relationships was introduced (1). In the initial form of analysis, the times the earth crosses solar magnetic sector boundaries (2) was utilized as "key days" in superposed epoch analysis. The initial study suggested that U.S. thunderstorm frequency maximized at or shortly after the earth crossed from positive to negative sectors. Exploiting this approach, Wilcox et al. (3,4) subsequently found that the vorticity area index (VAI), developed by Roberts and Olson (5) as a measure of the integrated hemisphere-wide state of the atmosphere, contained a

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characteristic variation (signal) which maximized one day after solar sector crossings. These VAI results, which appeared to be highly statistically significant, were widely reported, discussed, and confirmed by others (6); they provided a major factor in rekindling interest in the classic sun-weather problem.

If the interplanetary magnetic field is related to meteorological processes, what might the physical mechanism be? It is unlikely that the sector boundaries in themselves can directly affect the weather. Since the IMF is maintained and structured by the solar wind, and since atmospheric electrical processes seem to be the most probably link between solar variability and weather (in the author's opinion), variations in solar wind velocity have been examined relative to atmospheric electricity. This paper reports the first evidence linking the solar wind per se with a meteorological parameter. It has been found that solar modulation of the flux of ionizing radiation to the atmosphere is responsible for changing the intensity of the earth's fair-weather electric field; the latter is a meteorological parameter because it is maintained by worldwide thunderstorm activity. Enhanced stratospheric ionization and/or fair-weather electric field intensity may in turn affect thunderstorm electrification and thus possibly lead to cloud physical effects resulting in changes in the earth's albedo and transformations of atmospheric energy. These could affect air motions on all scales from convection in clouds to the general circulation.

Solar Modulation of Atmospheric Ionization

How does the interplanetary medium modulate electricity within the earth's atmosphere? In this regard the important characteristic of the IMF is that it controls the primary galactic cosmic radiation striking air molecules, and thereby the flux of secondary cosmic radiation generated mostly in the stratosphere. The latter is generally responsible for atmospheric ionization down to the top of the exchange layer (about 2 km above the earth). Below that level radioactive gases from the ground are about as important as cosmic rays in ionizing the atmosphere. Cosmic radiation is augmented at times by protons from solar flares which can penetrate down to the 20-30 km height range (7) and sometimes lower (8,9). It is well known that solar activity can modulate the flux of galactic cosmic radiation. Barouch and Burlage (10) have shown that magnetic blobs associated with rapid increases in solar wind velocity screen cosmic rays from earth. Figure 1 illustrates the decrease in cosmic radiation following a magnetic discontinuity corotating with the sun. A typical four-quadrant solar sector structure is also depicted.

The Global Circuit and Ionospheric Potential

Wilson (11) was the first to realize that the earth's electric field extends from its surface to the ionosphere and is sustained by currents driven by thunderstorm electric fields. If global thunderstorm activity were to stop, the atmospheric electric field would decay to near zero within an hour. This does not occur because thunderstorms are always taking place at various locations over the earth's surface (12). There is a global circuit, sometimes referred to as the "Wilson circuit", illustrated in Figure 2, in which the highly conductive upper atmosphere is maintained at a positive potential generally in the range of 200 to 300 kV relative to earth (13). In the non-thunderstorm (fair-weather) portions of the atmosphere a return path conduction current flows between the ionosphere and earth. The circuit is completed between the conducting earth and the bases of thunderclouds through a combination of conduction, convection, lightning, point discharge, and precipitation currents (14). One of the fundamental assumptions of the global circuit hypothesis is that the upper atmosphere (lower ionosphere) at about 60 km is so highly conductive that it can be considered an equipotential surface (14). Thus its electrical potential relative to earth should vary simultaneously all over the world. Experimental investigations have demonstrated that this is essentially true (15,16) except in and near the two Polar Cap regions (15% of the earth's surface) where magnetospheric and ionospheric generators can at times maintain significant horizontal potential gradients in the upper atmosphere (17). The conduction current can flow because the atmosphere is made conductive primarily through ionization by cosmic radiation. Electric fields in the fair-weather portion of the world are a consequence of the vertical air-earth conduction current flowing through the finite resistance of the atmosphere. Worldwide thunderstorm activity is generally accepted as the electrical generator of the global circuit since it is the primary agent charging the earth and the only one capable of transferring net charge to the upper atmosphere. Measurements of currents above thunderstorms have shown their sign and magnitude to be in agreement with the global circuit hypothesis (18). Thus, both theory and experiment have led most scientists working in atmospheric electricity to believe that the global circuit concept is essentially correct (19).

The Role of Atmospheric Electricity in Sun-Weather Relationships

In trying to understand how variable solar activity might influence weather, three basic questions can be formulated:

1) Where does the energy come from?
2) How does the energy reach the lower atmosphere?
3) If upper atmosphere heating is involved, how can the lower atmosphere respond as quickly as it does?

In view of these problems, several factors make an atmospheric electrical mechanism attractive. Because it is recognized that the energy output of the sun is essentially constant, i.e., less than the 1% accuracy of past measurements (20), it is not surprising that scientists are skeptical about the possibility that solar activity might affect the weather, at least on a shorter than climatic time scale. While the upper atmosphere above 120 km (the thermosphere) undergoes significant solar controlled temperature changes, this region is separated from the troposphere by two temperature inversions and essentially is cut off from the weather producing part of the atmosphere (21). However, the problems of energy and coupling can be bypassed with an atmospheric electrical mechanism in which potential energy already present in the lower atmosphere is released through electrically stimulated cloud physical processes--no upper atmosphere to lower atmosphere coupling is required. Below 25 km there is only one atmospheric parameter strongly and directly controlled by solar activity; this is ionizing radiation. Two time scales and types of radiation must be considered. In the secular time-frame there is an inverse correlation between galactic cosmic radiation and the 11-year sunspot cycle. Superimposed on this long term variation are short period changes lasting hours to days in which solar particles directly ionize the stratosphere.

Another factor favoring an atmospheric electrical mechanism is that of time delays. Some sun-weather studies show rapid atmospheric responses to solar variability; the vorticity area index (22) and atmospheric electric fields (23) both increase within one day following solar flares. A rapid atmospheric response to solar activity is difficult to explain in terms of present heating models of atmospheric circulation since these do not include atmospheric electrical effects.

The Atmospheric Electrical Sun-Weather Mechanism

Figure 2 illustrates how solar modulation of ionizing radiation would affect the overall intensity of the earth's electric field. This is the basis of a proposed sun-weather mechanism (24) that operates within the framework of the global circuit. The preceding reference describes why most of the resistance in the global circuit lies between the top of the thunderstorm generator (about 13 km at mid-latitude) and the ionosphere. This height range is accessible to the varying component of ionizing radiation (7,8,9). Equivalent radiation changes above 13 km in fair-weather parts of the global circuit (including the auroral oval) would have little effect on the flow of charge in the global circuit because the resistance in that element is relatively small. The arrows in Figure 2 are shown coming only as low as the tops of thunderclouds to illustrate that this is the height range where the variable component of ionizing radiation has access.

These factors have led to the conclusion that the resistive element over the global electrical generator can act as a valve controlling the current in the global circuit. Thus it can control the ionospheric potential and the intensity of the earth's electric field. If, as reported by Vonnegut et al. (25), the vertical conduction current over thunderclouds flows mostly over the turrets where an electrical screening layer is swept away by the unfolding mo on of the cloud surface, then the current would flow only over a small fraction of the cloud top. This would increase the resistivity of the charging resistor (possibly by an order of magnitude) and make it even more effective as the element controlling the global circuit current.

While cosmic radiation affects ionization down to the earth's surface, it is believed that solar flare particles generally do not penetrate to below about 20 km (7). However, balloon measurements following solar flares indicate that solar protons can enhance conductivity by an order of magnitude down to 15 km (8) and on occasion right to the earth's surface during "ground level events" (8). Even if the ionizing radiation penetrates only into the 20-30 km height range over thunderclouds, the charging resistance would be decreased sufficiently so that the charging current would be increased. The result would be an amplification of fair-weather electric field intensity throughout the atmosphere from the ionosphere to the ground and from pole to pole. Further discussion of solar controlled variations of atmospheric ionization (including an explanation of why stratospheric variations are much greater and generally in the opposite sense than ground level "Forbush decreases") is given in Reference 26.

An amplified fair-weather electric field and/or enhanced conductivity in the lower stratosphere introduces the possibility of positive feedback through increased cloud electrification. With either the convective theory of cloud electrification (27) or any of of the inductive charging mechanisms, the ultimate electric field intensity in a thundercloud depends on the initial electric field strength in the ambient fair-weather environment of the developing cumulus cloud. Thunderstorm electric fields in turn may play an important role in cloud microphysical processes (24). The above sequence suggests a way in which atmospheric electrical variations modulated by solar activity could influence atmospheric dynamics.

Evidence that Solar Variability Modulates the Earth's Electric Field

Figure 3 summarizes statistical studies which show a rapid increase in ionospheric potential following within one day of solar flares. These data from Reiter (top) and Cobb (bottom)(23) suggest a short term direct solar influence on atmospheric electrification caused by solar corpuscular radiation from solar flares (28).

The long term indirect effect due to modulation of galactic cosmic radiation is illustrated through the results of the balloon sounding program of Olson (29), summarized in Figure 4 (top). These data show a negative correlation between the fair-weather air-earth conduction current density (driven by the ionospheric potential) and the sunspot number. These data are divided into two sets depending on whether the soundings were made in the time interval centered on maximum or minimun of the universal time diurnal variation of ionospheric potential (30). The middle part of the figure is a scatter diagram of the 1100-2200 U.T. data set. The correlation coefficient r = - 0.667 has a confidence of 98.9% of it not being due to chance (31). The bottom part of the figure presents the scatter diagram for the 2300-0800 U.T. data; r = - 0.742 and here the probability has a confidence of 99.7%. Since galactic cosmic radiation is inversely correlated with the 11-year sunspot cycle and this radiation is the source of atmospheric ionization, Olson's measurements support the conclusion that increased ionization causes a rise in ionospheric potential in agreement with arguments presented in the proposed atmospheric electrical sun-weather mechanism.

Because some have misinterpreted the proposed mechanism as postulating a solar controlled change in thunderstorm activity, it is emphasized that it only offers an explanation for how solar variability modulates the earth's electric field. The discussion of possible cloud physical and dynamic effects is speculative and offered to suggest additional possible consequences.

New Findings Relating the Solar Wind to Atmospheric Electricity

In order to investigate how the interplanetary medium might be modulating the earth's electric field, the ionospheric potential variation was correlated with the basic property of the solar wind, its velocity, and a highly significant inverse relationship was found. Since the solar wind in itself can have no direct effect on ionospheric potential (32) and atmospheric ionization is maintained mostly by galactic cosmic radiation, the relationship between solar wind velocity and cosmic radiation was also analyzed and it was found that these too had a strong inverse correlation. Thus the ionospheric potential and associated intensity of the fair-weather atmospheric electric field vary in phase with atmospheric ionization.

The solar wind data were measured by a series of satellites and compiled at the NASA Goddard Space Flight Center (33). The ionospheric potential measurements were obtained by the author in a past field program (15). A series of 120 potential gradient soundings were made with an aircraft and from these estimates of ionospheric potential were obtained; these data have been documented previously (34). Of these soundings, 60 were made at the same times that satellites recorded values of the bulk solar wind velocity. Figure 5 is a scatter diagram depicting the correlation between solar wind velocity and ionospheric potential. The solid regression line represents all 60 data points and shows a negative correlation $r = -0.509$ with a statistical confidence of 99.99%. Because the group of points on the right of the diagram may be regarded as somewhat removed from the main body of data, suggesting the possibility of lack of normality in the distribution, the anaysis was repeated excluding those points with velocities greater than 500 km s^{-1}. The resulting dashed regression line has a correlation coefficient $r = -0.449$ with a confidence level of 99.95%.

Since many of the soundings were made on the same day, there would be some persistence in both parameters, i.e., they would tend not to change as much over a short time span (hours) as they would over a longer period (days). This is a classical feature of meteorological statistics and it introduces some uncertainty regarding the degrees of freedom, necessary information in testing the correlation for significance (35). In order to remove this uncertainty, the data have been grouped into single days, or sets of consecutive days, and then the average value of all ionospheric potential estimates within a group and average of corresponding solar wind velocities were correlated. The grouping resulted in 15 sets of average values. These represent soundings obtained a minimum of 2 days apart, and this only twice, with the remaining time intervals being longer. Since it has been found through an autocorrelation analysis of the daily U.S. thunderstorm index that there is no persistence beyond 2 days (36) these grouped data points should be independent. The scatter diagram for the grouped data is presented in Figure 6 ($r = -0.739$; $p > 99.95\%$). The correlation of these data is most easily visualized in Figure 7 made by plotting them chronologically with the solar wind velocity scale inverted because of the inverse relationship.

It is possible to investigate how solar wind velocity might be modulating ionospheric potential by examining its relationship to cosmic radiation. For this analysis the bulk solar wind velocity was correlated with cosmic ray data from the Mt. Washington neutron monitor (37). To obtain a reasonably large data base for each year it was necessary to use solar wind data for days with fewer than 24 hourly values listed. Inspection of the data showed that generally an average of as few as 21 hourly values gave a figure which was reasonably representative of the day's average. If as few as 18 hourly values were used, significant errors in the average sometimes occurred. Thus daily averages of solar wind velocity were calculated only for those days which had 21 or more hourly values listed. Data from 1967 and later were used as the earlier data were too sparse.

Table 1 shows the findings of this correlation study which covers almost a solar cycle period. On every occassion there is a negative correlation between solar wind velocity and cosmic radiation, although in 2 out of the 10 years the correlation is not significant. However, there is little question regarding the validity of the relationship. These findings are consistent with ideas suggesting that both solar wind and cosmic ray variations are associated with magnetic "blobs", or discontinuities, in the IMF (10).

Since the bulk solar wind velocity correlates negatively with both ionospheric potential and cosmic radiation, ionospheric potential varies in phase with cosmic radiation. This is in agreement with the arguments discussed previously suggesting that enhanced ionization would increase the current flow between thunderclouds and the ionosphere and thereby increase the electrification of the atmosphere.

An Experimental Approach to Investigating Atmospheric Electrical Sun-Weather Relationships Based on Measurements of Ionospheric Potential Variation

By measuring the earth-ionosphere potential difference, it is possible with just one instrument at one location to characterize the intensity of the earth's electrification over its entire surface (exclusive of local effects such as proximity to thunderstorms, blowing dust, and on occasion the aurora). This is because of the synchronous worldwide variations of the earth's electric field which have been verified (15). This characteristic offers the possibility of following the temporal variation of atmospheric electrification and thus opens up a new dimension of the atmosphere for study. Inasmuch as we routinely monitor electrical conditions on the sun and in space, it would seem we are remiss in not continuing such measurements within the earth's atmosphere. Even if solar variability did not affect atmospheric electricity, monitoring ionospheric potential and stratospheric conductivity on a routine basis would provide a more complete description of the state of the atmosphere.

The elegance of this approach can be appreciated by comparing it to the procedure utilized to define the earth's weather patterns such as pressure and vorticity fields. To obtain these, hundreds of simultaneous balloon soundings of temperature, humidity and the horizontal wind vector are made every 12 hours. The term "synoptic" used in meteorology arises from this requirement for many simultaneous measurements over a large grid. By adding a few additional radiosondes, but ones which measure the vertical electric field, conductivity and ion production rate, we would be able to characterize the state of the earth's electric field and atmospheric ionization, thus providing new key global parameters to our observations of the atmosphere. Such measurements would provide the desired record of ionospheric potential and stratospheric conductivity variations with a temporal resolution dependent on the frequency of the soundings. These could be compared to solar-terrestrial parameters which are routinely monitored such as solar flares, proton events, sector crossings, and solar wind characteristics. It would be advantageous to make these soundings on a frequent and routine basis during periods of unusual solar activity. The objective of such a program would be to identify the radiation, interplanetary medium conditions, and processes by which solar variability modulates atmospheric electrification. It would be necessary to obtain a long, preferably unbroken, time-series of ionospheric potential variation made at least once a day. The universal time diurnal variation of ionospheric potential component could be minimized by making the measurement at the same time every day--ideally at 0400 U.T., at the minimum in this cycle when it changes least in time. Such a time-series would constitute a <u>geoelectric index</u> patterned after, complementary to, and used in the same fashion as the geomagnetic index which has been of great importance in solar-terrestrial research. The desirability of a continuous time-series arises from the requirement for cross-correlation with other geophysical parameters; breaks in time-series seriously degrade their value in correlation studies.

A complementary approach to achieve fine time resolution of the variation of ionospheric potential would be to use the previously demonstrated technique of recording the variation of vertical potential gradient from a constant altitude aircraft (15) or balloon platform stationed in a favorable environment (low noise) well above the atmospheric exchange layer. This approach would provide a continuous measure of the variation of ionospheric potential. To obtain its magnitude periodic soundings would be required. This could be done by lowering and raising the tethered balloon (or kite) which supports the atmospheric electrical radiosonde used for the continuous measurement. Alternately, a potential gradient sounding could be made with a free balloon. In a favorable environment the tethered balloon or kite would have to be raised to a minimum of 5 km (38). Such measurements could most easily and reliably be conducted from a ship at sea, but they would be more difficult and expensive than free balloon soundings. Their great advantage would be in providing a continuous real-time measure of the earth's overall electric field variation (39).

Lightning Detection from Satellites

The ability to observe the earth from space offers for the first time the possibility of determining the spatial and temporal variation of global thunderstorm activity. Photoelectric systems are capable of sensing lightning during the day as well as at night (40). Since there is high probability that optical sensing alone will not detect much of the lightning from the middle and lower portions of deep clouds, it will be necessary to sense lightning generated electromagnetic radiation at other frequencies as well. A new interferometric technique seems particularly attractive for this purpose (41). Three or more geostationary satellites could give the required full time coverage of most of the earth's surface (42).

While lightning frequency and intensity must be some sort of indicator of the electrification of clouds, it should not be assumed that a simple correlation exists. It will be necessary to define such relationships. The ability to sense ionospheric potential and thundercloud electrification simultaneously on a global scale will provide a breakthrough in our ability to evaluate the global circuit hypothesis. It will also offer the means for testing the proposed atmospheric electrical sun-weather mechanism including the speculative part in which cloud electrification may be influenced by solar controlled changes in atmospheric electricity.

Relevance to SCADM

Both the ionospheric potential and satellite lightning measurements have been proposed. The forthcoming Solar Cycle and Dynamics Mission and associated plans for studying the solar cycle from space will provide an ideal time frame to initiate these studies of the relationship of the sun and interplanetary medium to atmospheric electrification and weather.

Acknowledgment

Support for this research was provided by the Atmospheric Science Program, Office Of Naval Research, under Contract N00014-79-C-0399.

TABLE 1

YEAR	AVERAGE SUNSPOT NUMBER	DAYS WITH AT LEAST 21 HOURLY SOLAR WIND VALUES	CORRELATION COEFFICIENT	SIGNIFICANCE LEVEL
1967	94	244	-0.338	< 0.01
1968	106	198	-0.106	
1969	106	184	-0.342	< 0.01
1970	105	121	-0.338	< 0.01
1971	67	96	-0.328	< 0.01
1972	69	136	-0.495	< 0.01
1973	38	259	-0.444	< 0.01
1974	35	337	-0.197	< 0.01
1975	18	140	-0.055	
1976	12	178	-0.272	< 0.01

The yearly correlations between solar wind velocity and cosmic radiation (Mt. Washington, New Hampshire neutron monitor data). The negative correlations imply that increasing solar wind speed results in decreasing cosmic ray flux.

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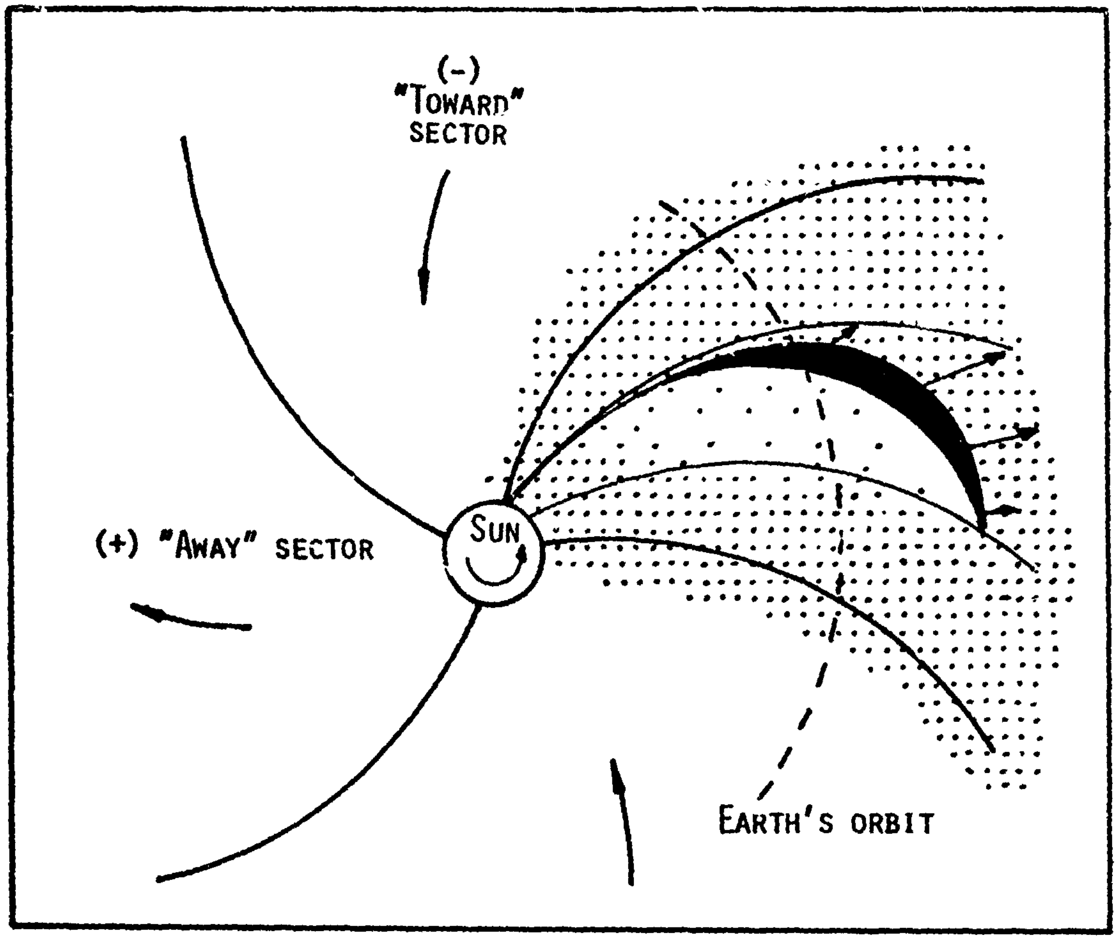

Fig. 1. Idealized magnetic blob (black region) moving radially away from sun with velocity indicated by arrows, (after Barouch and Burlaga (10)). Two spiral magnetic field lines bounding the blob are shown within one sector. A typical 4-quadrant sector structure is also depicted. The dots (shown for one sector only) represent the conjectured cosmic ray intensity.

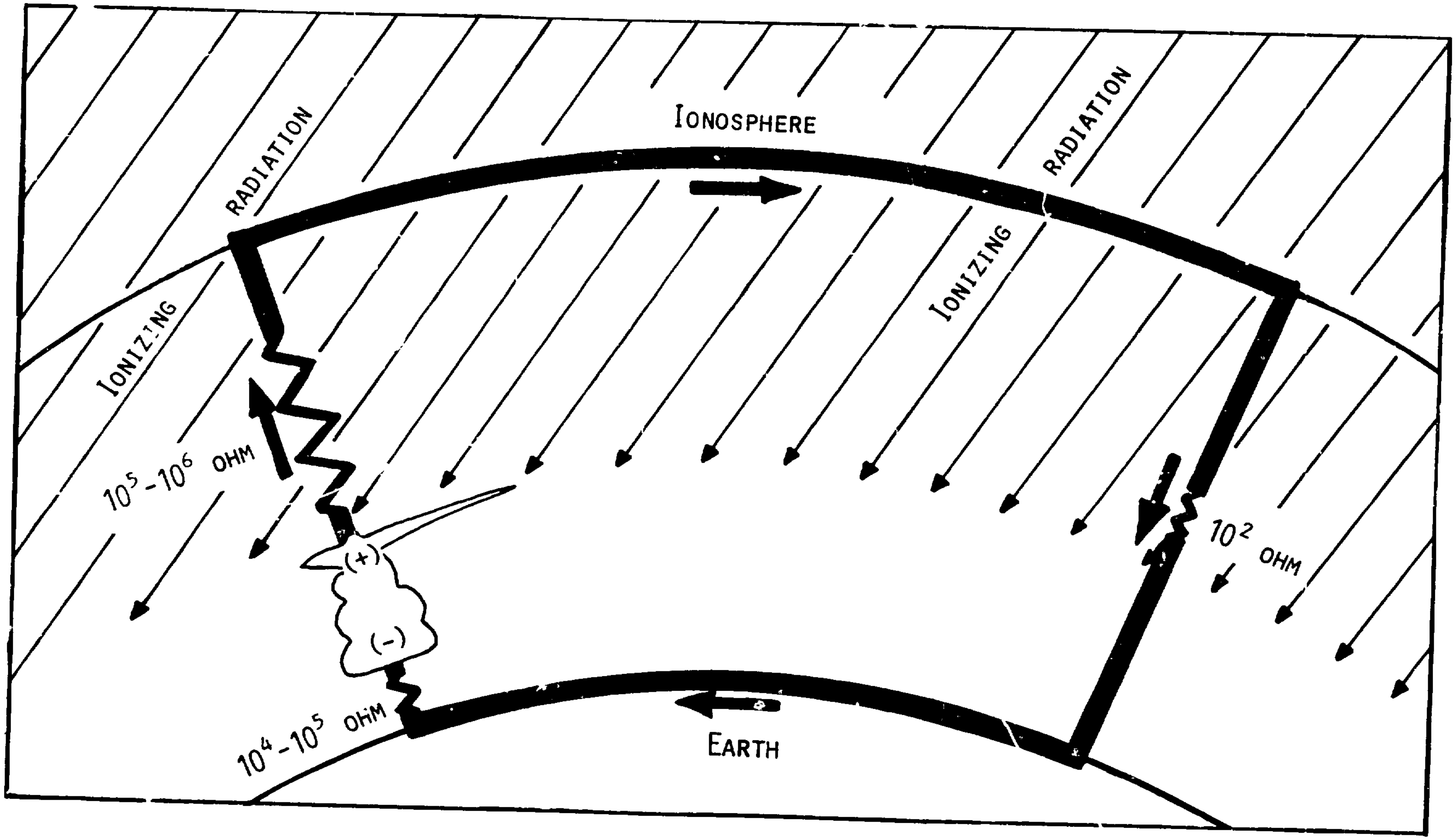

Fig. 2. Schematic of the global atmospheric electrical circuit illustrating relationships between resistive elements and showing accessibility of controlling resistive element above the thunderstorm generator to the varying component of ionizing radiation (after Markson (24)).

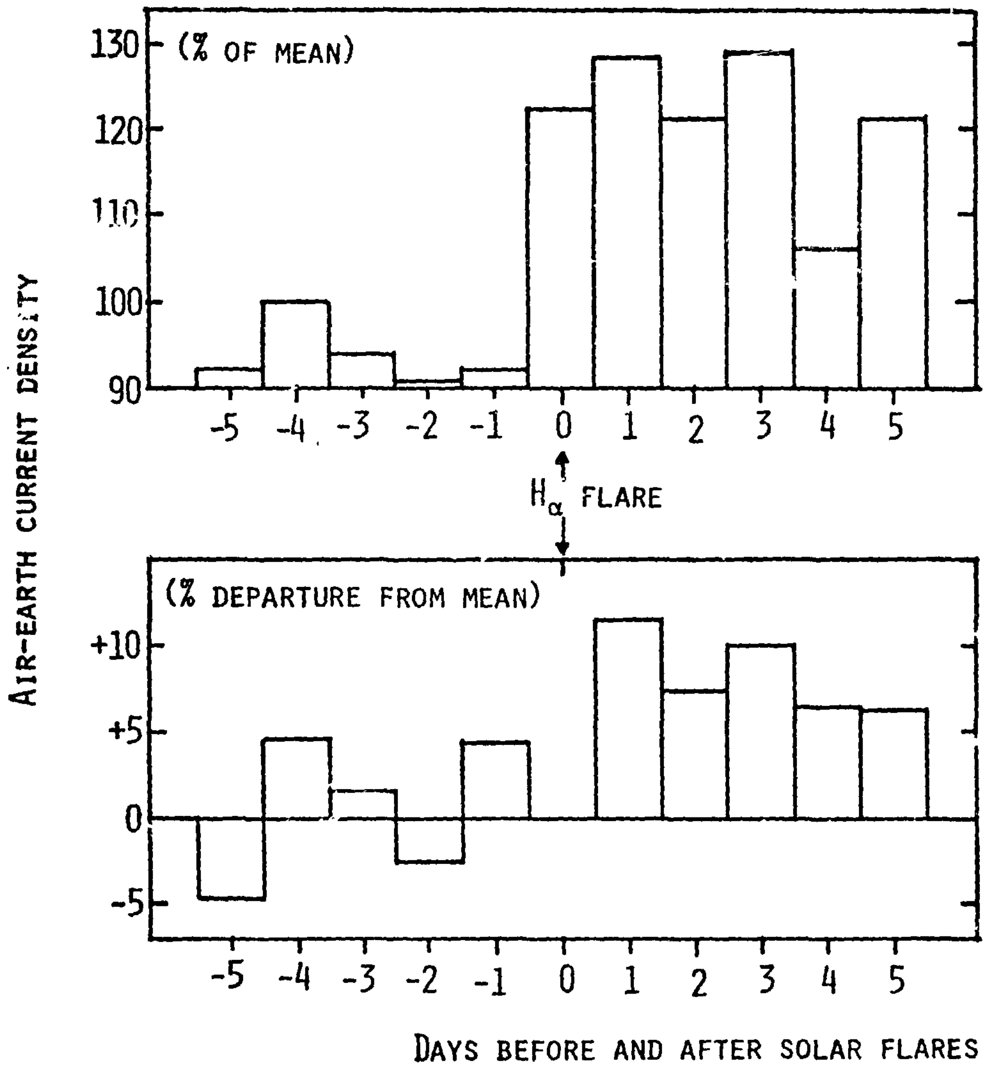

Fig. 3. The variation of air-earth conduction current density before and after the occurrence of solar flares showing the rapid increase in ionospheric potential. The upper figure is a composite of Reiter's data obtained on the Zugspitze mountain peak in Bavaria taken from both references in (23) to maximize the data base; the lower figure summarizes the analysis of Cobb (23) using measurements from Mauna Loa volcano in Hawaii.

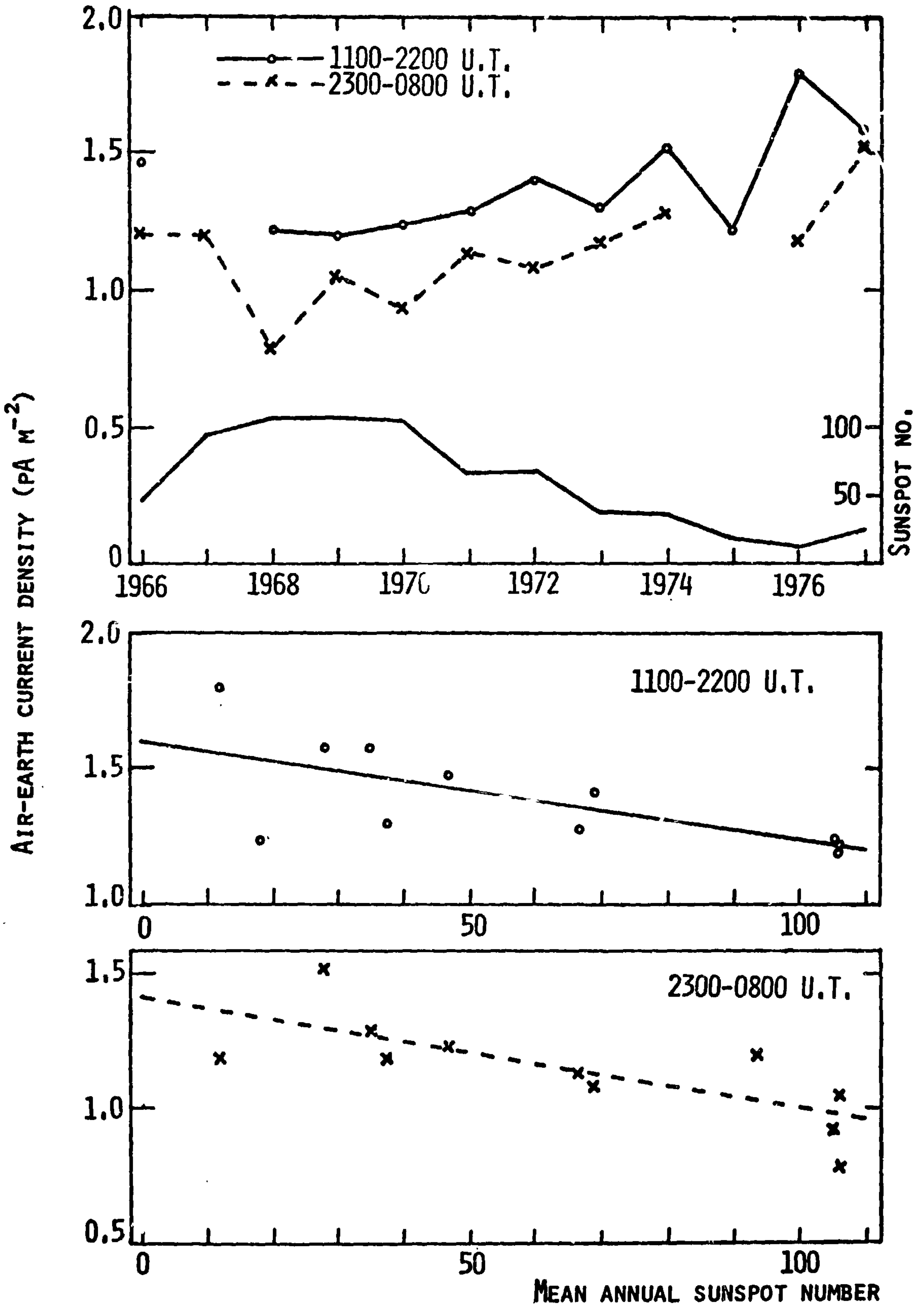

Fig. 4. The variation of air-earth conduction current density (a measure of ionospheric potential) through a solar cycle. Over 300 balloon ascents provided the data base; D.E. Olson, Univ. Minn., Duluth (Ref.29).

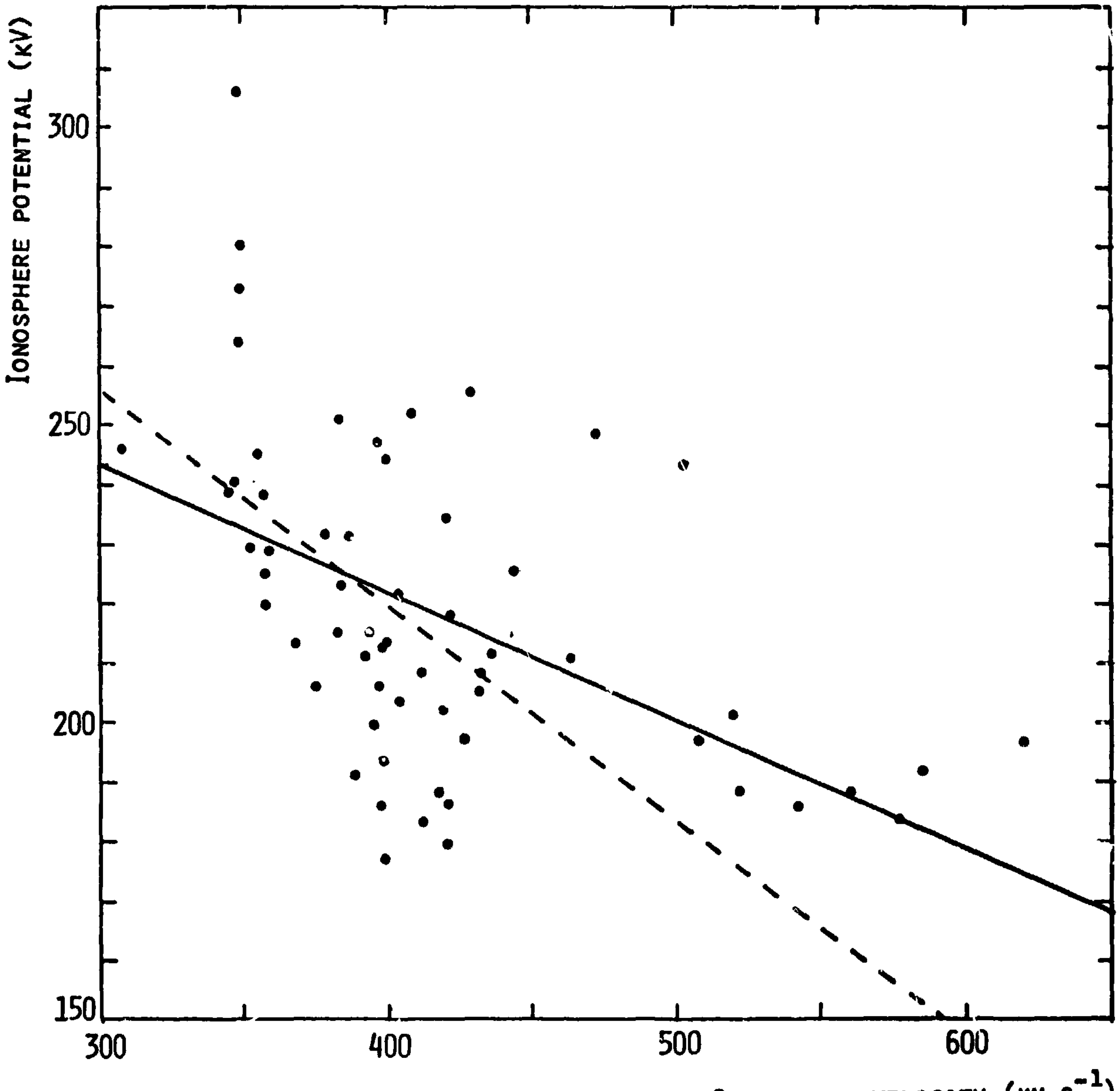

Fig. 5. Scatter diagram showing the relationship of ionospheric potential to solar wind velocity. The solid regression line refers to all the data points (n = 60), the broken line is for the data when those points with velocities greater than 500 km s^{-1} are excluded (n = 51).

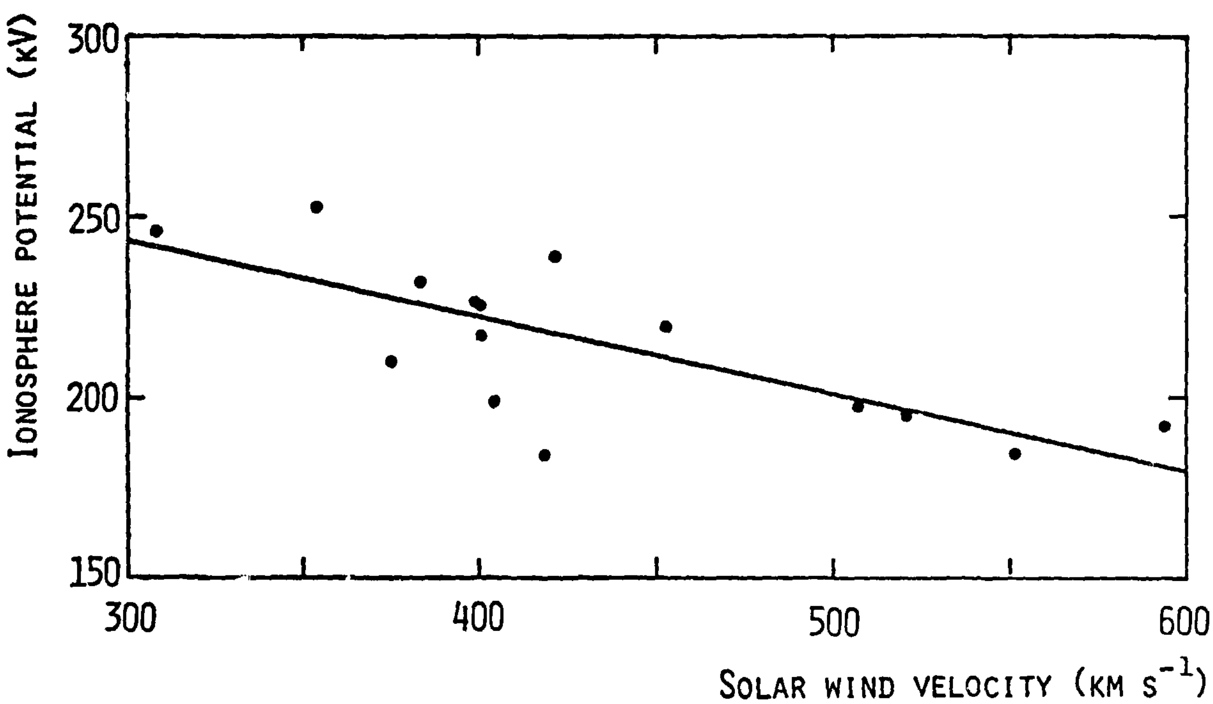

Fig. 6. Scatter diagram showing the relationship between averages of grouped ionospheric potential measurements and corresponding solar wind velocities. This was done to insure independence of the data (see text). The points represent groups separated from each other by at least 2 days to eliminate possible effects due to persistence.

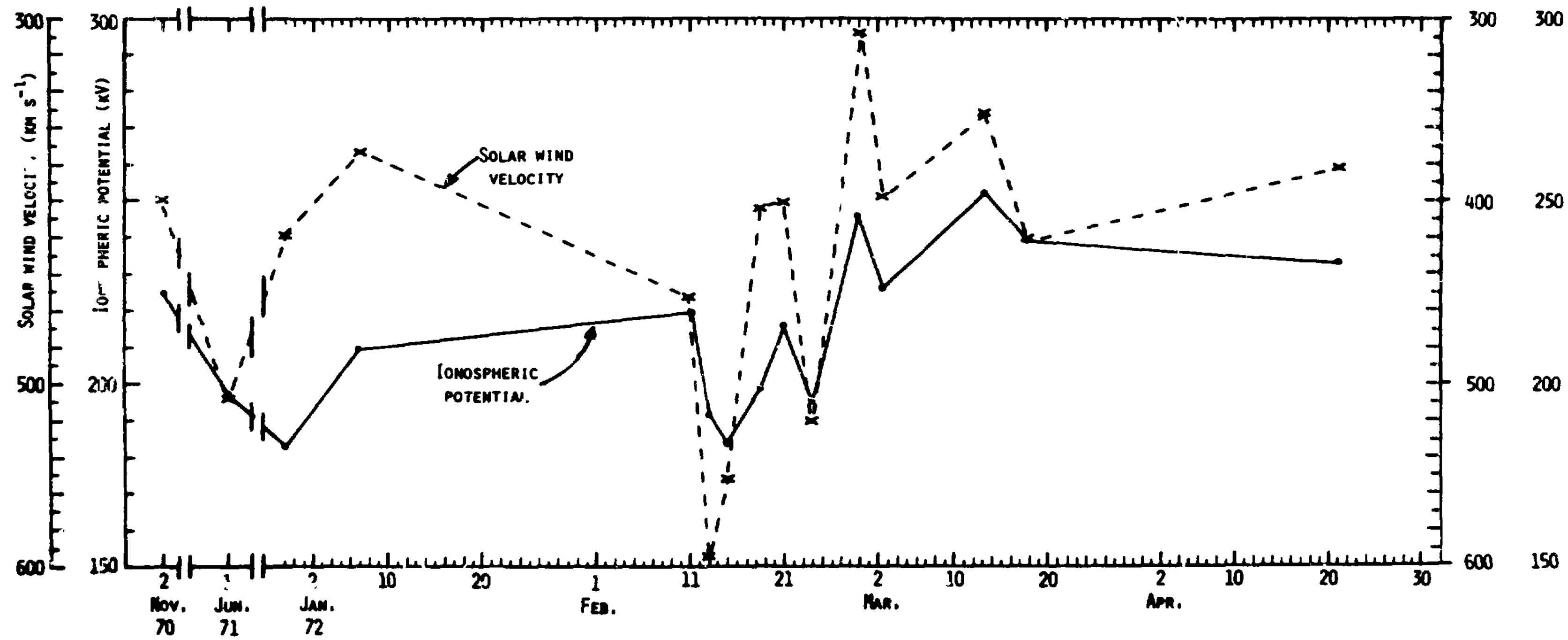

Fig. 7. Correlation between simultaneous measurements of ionospheric potential and solar wind velocity (the grouped data of Fig. 6). Solar wind velocity scale is inverted to enhance visualization of the negative correlation.

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SUMMARY OF THE SCADM MEETING

14-15 June 1979 Wellesley, MA

Jack B. Zirker

The Symposium on the Study of the Solar Cycle From Space was convened to provide a forum for the discussion of a new program in solar terrestrial physics. The program has been under discussion by a special working group, chaired by Gordon Newkirk, for some months. This was the first opportunity for the solar community to participate.

The scientific objectives of the program were outlined by Robert Noyes. The program is primarily intended to investigate mechanisms of the solar cycle using a combination of ground-based and space observations and theory. The program would last at least a decade and would aim at developing a *predictive* theory for the solar dynamo sufficiently accurate to forecast large scale variations in the sunspot cycle and its associated activity cycle, to understand previous dramatic fluctuations in amplitude of the cycle (such as the Maunder minimum), and to calibrate geophysical proxy data that would allow us to extend back for several thousand years the record of solar output variation and their influence on the terrestrial environment.

Noyes pointed out that these objectives are eminently practical, that the field is ripe for exploitation and that the program would impact both stellar astrophysics and geophysics. The program is especially appropriate at this time for a variety of reasons. Evidence is continuing to accumulate that the sun is far from being the constant source of light and solar wind that we have always imagined. Its rotational rate

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and luminosity may change with time, and as reported at the AAS meeting at Wellesley, even its radius may be changing with time! The Skylab Mission revealed new connections between the evolution of the corona and the deep-seated dynamo that controls the solar magnetic field. New techniques for studying the interior of the sun, its large scale pulsations and its general circulation have been devised recently and although they need further development, they give us new tools with which to study the physical basis of the dynamo. Finally, the application of large scale computers to the modeling of the solar dynamo in recent years has given theorists the confidence that they are on the track of understanding some of the basic mechanisms.

In the middle of the late 80's, NASA is considering several space missions which, if supplemented by a specific Solar Cycle and Dynamic Mission (SCADM) would work together in an unparalleled opportunity for coordinated investigations of the solar dynamo, its effect on the heliosphere and its effect on the earth. These missions include OPEN, UARS and Solar-Polar.

In order to devise a program for the investigation of the solar cycle, it is necessary to begin with the current status of dynamo theory. Nigel Weiss reviewed our present understanding of the solar interior, its effect on the generation of solar magnetic fields and the prospects for further progress with the SCADM. The first objective of theorists is to develop a dynamo theory capable of predicting the normal phenomena associated with the eleven and twenty-two year solar cycles. *Kinematic* theories of the dynamo have been developed in great detail. In these, the interior motions of the sun are postulated and their consequences explored. These have been valuable in showing how the eleven-year period arises, how the butterfly diagram develops and how Hale's law of polarity arise. To progress further, theorists need to develop realistic models of how the interior motions of the sun are maintained by the interaction of convection and rotation, and how these motions produce not only the steady-state eleven-year cycle but also the fluctuations such as the Maunder minimum. Such *dynamical* models have progressed rapidly in the past decade. The models are still not capable of treating the full range of variations of physical parameters (temperature, density) that occur on the sun. And they still involve physical approximations, such as the concept of turbulence diffusivity, that can be challenged. Nevertheless, the dynamic models are a tremendous improvement over the kinematic models.

To progress further, however, dynamo theorists need observations to guide them. In particular they need (a) observations that reveal the structure of the deep interior (at the present time the neutrino flux deficit is only one of several possible observational approaches to fulfilling this demand), (b) observations of the structure and circulation of the convection zone, (c) observations of the large scale magnetic field and its evolution in space and time, (d) evolution of the small scale magnetic field. We have come to recognize over the past decade that the surface of the kinetic fields of the sun are concentrated in extremely small, intense flux tubes and that the interaction of the field with the gas occurs at this scale and not on the large scales which dynamo theory presently considers. The theory must be refined to take into account the generation of the flux ropes beneath the surface, the emergence of such ropes to produce bipolar magnetic regions, i.e. sunspot groups, the transport of the flux over the surface and the dissipation and reconnection of the field near the surface. To develop these aspect of the theory, observations on the small scale structures with s les down to an arcsec are needed.

In addition to these observational inputs the theorists also need of course to develop their tools for handling more realistic physical situations, such as compressible gas, magnetic buoyancy, realistic values of the Reynolds and Prandtl numbers, convective turbulence and other phenomena.

This short list of observational requirements for the further development of dynamo theory can be converted into a list of typical experiments to be carried out, either from a space vehicle (SCADM) or from the ground. Each of these experiments can be justified and related to a specific observational requirement, as outlined above.

There are three classes of experiments that can be conceived. The first relates to the description of the structure and motions of the interior and convection zone, the second to the surface interaction of magnetic fields and velocity fields and the third, to the evolution of coronal structures which serve as tracers for the large scale magnetic field and therefore like sunspots, for the patterns that a dynamo theory must explain.

Timothy Brown examined a number of experiments in each of these categories from the standpoint of the ultimate limitations on accuracy that could be obtained either from space or from the ground. He focused on the sources of noise for particular measurements and on the effects of interruptions in a time-string of observations on the ultimate resolution that is obtainable either from the ground or from space. From these considerations he was able to make recommendations on which experiments are most appropriate for spacecraft. Brown listed typical experiments, as follows:

1. Large Scale Flows
    a. The detection of time and latitude variations in the solar rotation.
    b. The detection of meridional flow and the investigation of its spatial and temporal organization.
    c. The detection of the largest conceivable convective cells ("giant cells") from their Doppler signature, and the study of their physical properties.

These experiments are all characterized by low spatial resolution, low time resolution but extremely high velocity sensitivity (less than 1 m/s) and a requirement for stability of velocity measurements for at least two weeks and preferably, several months.

2. Oscillations
    a. Depth variation of rotation.
    b. Structure of the solar interior.

The depth variation of angular rotation in the convection zone has been revealed from the Doppler splitting of the five-minute photospheric oscillations. This work is calable of considerable extension and refinement and Brown investigated what kind of observational conditions must be satisfied. The structure of the interior, now revealed only by the neutrino deficit, can be studied in principle by using the resonant oscillations of the whole sun. These fall in the period range 20-160 m and such oscillations have already been detected marginally from the ground.

3. Chromospheric and Coronal Tracers
   a. Holes, XBP
   b. UV Luminosity

Brown's final category of experiments involve chromospheric and coronal tracers of the large scale magnetic field that in turn serve to constrain the dynamo theories. Such features as coronal holes and X-ray bright points would require X-ray observations from a satellite. The variations in the UV luminosity of the sun also serve as important datum for the development of dynamo theories.

Brown assumed in his investigation that the SCADM satellite would fly in a low-inclination near-earth orbit and so suffer eclipses for half the time every ninety minutes. With this basic assumption he was able to place experiments in categories according to whether a space observation was *essential*, gave *marginally* increased benefits, or was *not essential*. In the first group of essential experiments were: the detection of global oscillations (with amplitudes of 1 m/s), the detection of giant cells, the determination of the azimuthal mode structure of the ridges of the five-minute oscillations and the monitoring of X-ray bright points and coronal holes. In the second category (where space gives only a marginal advantage) was the determination of the angular velocity as a function of depth in the convection zone from the five-minute oscillations, the monitoring of magnetic field tracers such as supergranulation and the monitoring of EUV luminosity. Oscillations of the solar diameter and chromospheric magnetic tracers can be done as well from the ground.

Dave Bohlin reported the good news that a polar mission for the SCADM is now feasible at an incremental cost of perhaps 30%. Such a polar mission would alleviate or eliminate many of the intrinsic problems of detection that Brown uncovered so that in effect, Brown's study serves as a scientific justification for the value of a polar orbit.

Art Hundhausen reviewed the variation of the corona and wind with the solar cycle. A very clear and simple picture for this evolution has come out of Skylab observations and the follow up that has been done since then. Coronal holes, as sites of open magnetic fields and fast solar wind, reach their maximum size and stability just before solar minimum. The sun is then dominated by two huge polar holes with no mid-latitude or polar extensions. This characterized the solar minimum around 1976. The large scale magnetic field of the sun was roughly dipolar with a neutral current sheet extending from closed magnetic field lines that straddle the solar equator and extending out into the heliosphere. As the sunspot cycle picks up, the polar holes shrink and mid-latitude holes develop. At maximum sunspot activity, the polar holes virtually disappear and large mid-latitude holes develop, some with the same polarity on opposite sides of the equator. This simple evolution, together with the rigid rotation of coronal holes, and (at least during Skylab), the systematic eastward progression of new coronal holes must be explained by any acceptable theory of the dynamo.

Hundhausen met head on the question: Why make more coronal hole observations when Skylab did such a fine job? There are several reasons. First, Skylab was as successful as it was mainly because a great variety of data (X-ray, white light, interplanetary wind) were available to put together a complete three-dimensional picture of coronal evolution. But Skylab occurred during solar minimum and we now have no prospects for obtaining as complete a picture during solar maximum. Secondly, the simple picture of the heliosphere that emerged from Skylab must be checked with observations out of the ecliptic since the model is based on extrapolations. Third, there is no reason to suppose that the last cycle was typical: we would like to be sure that the regularities observed during Skylab are an essential feature of the solar cycle!

Len Fisk reminded us of the accumulating evidence for a connection between climate changes on earth and variations in the solar outputs that are associated with the solar activity cycle. This connection is controversial, but offers a tremendous practical stimulus for understanding, in a physical, predictive theory, how the sun influences the earth's climate.

In summary, the SCADM Symposium convinced all of us that the time is right for an evolutionary study of the mechanisms of the solar cycle, employing ground and space observations, for a development of new theory, with the purpose of understanding not only the steady-state behavior of the solar activity cycle, but also its temporal fluctuations on scales ranging from 100 to 500 years. Such a study would have enormous practical benefits not only to the development of solar research and for the understanding of activity cycles on other stars, but also in our predictive power to anticipate and therefore prepare for variations of the terrestrial climate that are driven ultimately by the solar dynamo.

QUESTIONS AND COMMENTS

COMMENT BY: N. Gerson, Laboratory for Physical Sciences

DIRECTED TO: J. Zirker

The scope of the Conference and the detail of many of the papers were impressive. Nonetheless, I feel that three topics of some interest could have been more fully explored. These include, (a) priority of the needed research, (b) the solar wind and magnetic field, and (c) the potential of a lunar astronomical observatory. Comments on each topic are given below.

(1) Priority of the Needed Research. Most investigators seemed to promote their particular project. Even at the conclusion of the conference there was no clear list of priorities for research projects. If NASA were to allow only a single experiment, which one would be the overwhelming choice of the Conference? If NASA were to allow, two, three...etc., which would be chosen? What importance do solar physicist themselves place upon their research? A choice must, of course, consider three critical spacecraft limitations: (a) the orbit, (b) the allowable weight and mass, and (c) the bandwidth of the downlink telemetry.

I believe that the majority of the audience felt that each experimenter considered his research to be the most important. However, such an approach is unrealistic in view of the competition for dollars and volume aboard the spacecraft. To me, if not for NASA, the group must list the value and priority of proposed investigations.

(2) Solar Wind and Magnetic Fields. Three bodies of the solar system contain appreciable magnetic fields: Earth, Jupiter and the Sun. In flowing past the magnetospheres of the planets, the solar wind compresses the sunward field, stretches the nocturnal field, and produces strong solar associated changes in the radiation belts, magnetic fields, ionospheres and auroras.

The solar wind acting upon the solar magnetic field also would distort and stretch the field lines, and perturbs the solar magnetosphere (which basically should be a cavity in the galactic wind). It is conceivable that ejected material, returning to the photosphere, would be trapped in deformed radiation belts and dribble onto the surface in two zones analogous to the planetary auroral ovals. To what extent has this possibility been treated or observed?

(3) Lunar Astronomical Observatory. In today's technology an astronomical observatory on the moon is not unrealistic. Considering initial installation costs, lifetime, platform stability, what are the trade-offs between an artificial satellite and a lunar-based astronomical observatory?

COMMENT BY: J.L. Linsky, JILA/University of Colorado

DIRECTED TO: J. Zirker

I would like to make some comments concerning the concluding remarks by Jack Zirker.

(1) I strongly agree with Jack's conclusion that the dynamo processes, which presumably regenerate magnetic fields in the Sun, must be understood in order to understand the solar cycle.

(2) Dynamo processes pose an extremely difficult theoretical question, and to pursue this question theoreticians need the guidance of observations.

(3) Just observing the Sun, even with very sophisticated techniques, may be inadequate because the basic independent parameters have only one value. These parameters include gravity, rotational velocity, chemical composition, depth of the convection zone, age (insofar as it determines properties of the core), initial magnetic field configurations, etc.

(4) However, stars do exist which are in most ways similar to the Sum but differ in one or more of these independent parameters. As a result, it may be possible to test dynamo properties or obtain insight into dynamo properties by performing something similar to a controlled experiment. By this I mean studying a group of stars, including the Sun, which differ mainly in one of the above parameters. Observables which might be studied include emission line strengths for lines formed in chromospheres and transition regions, coronal X-ray emission, and magnetic field strength (when the technology improves to make this feasible).

(5) I therefore urge the continued and strengthened support by NASA of correlative studies of solar-type stars for the purpose of better understanding dynamo and other processes occurring in the Sun.

<u>COMMENT BY</u>: K. H. Schatten, Astronomy Department, Boston University

<u>DIRECTED TO</u>: J. Zirker

We have had a little trouble seeing the forest for the trees. There is, however, one theme which I see has recurred that a number of scientists feel should <u>not</u> be excluded in solar cycle dynamics studies. At this conference, it has been stressed by Drs. Rust, Hundhausen, Feynman, Crooker, Sheeley, Suess, Keller, Matsuka, and myself. It is the role of the solar magnetic field and its variability in governing subsequent solar activity. Dr. Rust has suggested a particular space experiment to better observe its growth and decay whereas Dr. Feynman has stressed the usefulness of geomagnetic activity parameters (which depend on recurrent solar wind streams in the latter half of a cycle governed by the sun's polar field) as a clue to long-term solar cycle fluctuations.

<u>COMMENT BY</u>: R. Levine, Harvard-Smithsonian Center for Astrophysics

<u>DIRECTED TO</u>: J. Zirker

I am surprised that in a symposium devoted to the study of the solar cycle, which is largely manifest in the magnetic field, there has been very little mention of observations of the field itself. Direct study of the solar magnetic field is crucial to the study of the solar cycle for two main reasons:

(1) High resolution magnetograms are an indispensible component of the study of turbulent magnetic diffusion, which is the key physical process in the solar dynamo.

(2) Using the observed fields to model the magnetic structure of the inner corona and interplanetary field is potentially the most reliable tracer of the position of open field lines in the corona. Careful analysis of measured magnetic fields can be used in conjunction with many of the techniques mentioned by speakers at this symposium to improve greatly the understanding of the coronal response to the solar magnetic cycle.

NON - PRESENTED PAPERS

APPENDIX A

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CORONAL HOLES, SOLAR DIURNAL ANISOTROPY OF COSMIC RAYS AND OFF-ECLIPTIC INTERPLANETARY MAGNETIC FIELDS

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It is a well-known fact that most of the information regarding the broad features of the interplanetary magnetic field, prior to the space probes was derived from careful analyses of cosmic ray intensity variations observed with a global network of neutron monitors and muon telescopes, deployed over a variety of observing sites ranging from mountain tops to deep underground. The advent of space probe era has in no way minimized, at least thus far, the importance of this technique. Observations in free space have no doubt provided us with a lot of details as to the fine structure and temporal changes in the electromagnetic states of the interplanetary medium. There have not been too many surprises, however. This is because spacecraft observations have been confined to low energies, close to the plane of the ecliptic, at isolated points in space, for a limited amount of time. Many of these limitations are not likely to be overcome, at least in the near future. This criticism certainly applies to the spacecrafts which will be launched in the coming decade to probe areas far away from the ecliptic plane, inside the heliosphere. Recently it has become apparent that it might be possible to make inferences regarding the large-scale features of the interplanetary magnetic field, far away from the ecliptic plane, through the study of solar diurnal anisotropy of cosmic rays. Our results are discussed.

1. Introduction. I wish to take this opportunity to make a plea to the NASA administrators. I believe that they should seriously think about remedying an apparent flaw that presently exists in the planning aspects of a space mission. It is my considered opinion that when a mission is in the

planning stage and a long lead time is available, a non-trivial sum of money should be made available to encourage the relevant research efforts which may be directed towards obtaining mission related information, in an indirect manner, from ground-based observations. I believe that there are several appropriate active areas of research which may qualify for support. This morning I will describe one such area of research which is relevant to the objectives of the mission which is being discussed at this symposium. I already feel encouraged that the Study Group for Solar Cycle and Dynamics Mission (SCADM) considers it most important that ground-based observations be used in conjunction with this mission, over its lifetime, i.e. over a significant fraction of a solar cycle. This is a step in the right direction.

2. Cosmic Ray Research Using Worldwide Network of Detectors. It is a well-known fact that most of the information regarding the electromagnetic states of the interplanetary medium, prior to the space probe era, was derived from the careful analyses of the cosmic ray intensity variations observed with a global network of cosmic ray detectors such as neutron monitors and muon telescopes deployed over a variety of observing sites, ranging from mountain tops to deep underground. Alfven (1950) pioneered this approach by postulating the existence of magnetized solar beams in the interplanetary medium. He (Alfven, 1954) and his co-workers (Brunberg and Dattner, 1954) showed that such beams would modulate the cosmic ray intensity in the interplanetary space, in a characteristic manner. Notable contributions to this area of research were made by Davis (1955), Nagashima (1955), Morrison (1956), Dorman (1957), Gold (1959), Elliot (1960), Parker (1958, 1960, 1961), and McCracken (1962). It is indeed a tribute to the patience and the scientific wisdom of these and several other workers that when direct

measurements were finally made in the free space, broad notions regarding the meteorology of the interplanetary medium were found to be essentially correct. The advent of the space probe era has in no way minimized, at least thus far, the importance of the technique of continuous monitoring of cosmic ray intensity as a means of deriving information about the broad features of the interplanetary magnetic field. By no means do I wish to minimize the importance of the spacecraft observations in free space. The fact is that observations in the free space have provided us with a lot of details as to the fine structure and the temporal changes in the state of the interplanetary medium. But by and large there have not been too many surprises. One should note here the fact that spacecraft observations have essentially been confined to low energies, close to the plane of the ecliptic, at isolated points in space, for a limited amount of time. Most of these limitations are not likely to be overcome, at least in the near future, even when the spacecrafts begin to probe areas far away from the ecliptic plane, inside the heliosphere.

Recently (Ahluwalia, 1977a,b) it has become apparent that it might be possible to make inferences regarding the large-scale features of the interplanetary magnetic field, far away from the ecliptic plane, through the use of cosmic ray technique. As we have heard for the past two days, research workers concerned with the nature of solar magnetism are just now beginning to speculate about the overall structure of the interplanetary magnetic field at such far-off distances. An independent check of their ideas is absolutely essential. Hopefully we would thereby be led to an internal consistency in our broad scientific picture which may then in turn be examined for details by observations made aboard the spacecraft missions such as those being discussed at this symposium.

3. Solar Diurnal Anisotropy of Cosmic Rays. This afternoon I propose to demonstrate how the questions pertaining to the large-scale characteristics of the interplanetary magnetic field, far away from the ecliptic plane, may in principle be related to the temporal characteristics of the cosmic ray solar diurnal anisotropy. The commonly accepted model for this phenomenon emerged from the efforts made by myself and Dessler (1962), Parker (1964), and Axford (1965). The model

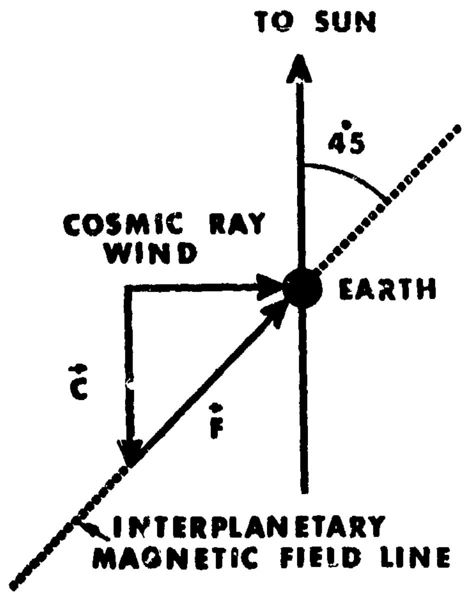

Figure 1

is illustrated in Figure 1. Cosmic rays tend to diffuse into the heliosphere along the interplanetary magnetic field lines, which on the average are inclined at an angle of 45° west of the earth-sun line, as indicated in the diagram. The cosmic ray flux along the field is indicated by the vector $\vec{F}$. At the same time cosmic rays are swept radially outwards by Alfven magnetized beams (commonly called the solar wind). It turns out that the radial flux of cosmic rays ($\vec{C}$) outwards is exactly balanced on the average, by the radial component of $\vec{F}$, resulting in no net radial streaming of cosmic rays within the heliosphere. A cosmic ray wind then naturally appears in the model. This is shown in the diagram. The net streaming is tangential to the orbit of the earth, i.e. the cosmic rays appear to corotate with the sun. A detector on the rotating earth therefore sees slight excess of cosmic rays arriving from the local dusk direction. This effect is commonly called Corotational Anisotropy of Cosmic Rays. It has a period of 24 hours in local solar time. It is a small effect. The amplitude of the sinusoidal variation, with local time, is about 0.5%.

When cosmic ray data, obtained at a given observing site, are averaged over a long period of time and subjected to the Fourier analyses three periodicities stand out. Figure 2 shows the power spectral density estimate (in arbitrary units) made from ten years (1962-71) of data obtained at Deep River with a super neutron monitor. Clearly there are well-defined peaks at 1-cpd, 2-cpd, and 3-cpd. As can be seen the peaks are highly significant. Note that cosmic ray diurnal variation (1-cpd) is by far the largest effect (note also that the power spectral densities at 1-cpd, 2-cpd, 3-cpd are approximately in the ratio of 800:20:1, respectively). I might point out that semidiurnal variation (2-cpd) is perhaps on the threshold of being understood. The tridiurnal variation was discovered only six years ago (Ahluwalia and Singh, 1973). At the present time no concensus exists as to its origin.

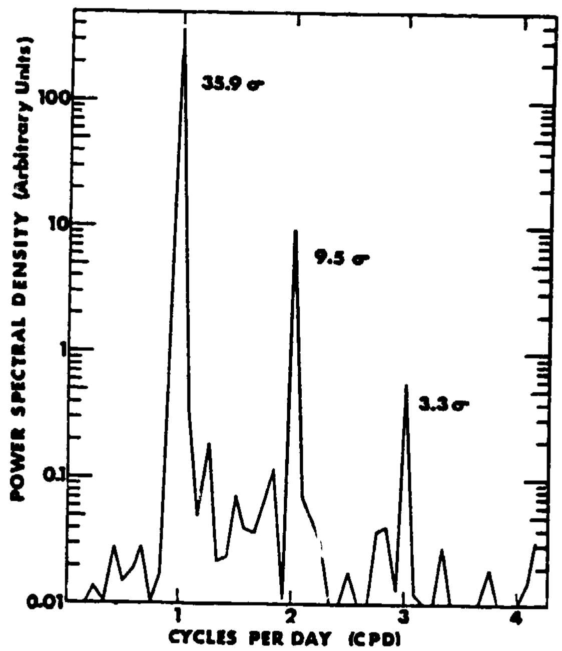

Figure 2

Figure 3 shows the year-to-year change in the times of maximum of the diurnal, the semidiurnal and the tridiurnal variations for the Deep River neutron monitor (black dots) and the University of New Mexico Vertical Muon telescope located underground at Embudo, New Mexico (circles with crosses).

The two detectors respond to different median rigidities (R_m) of the primary cosmic rays. For Deep River neutron monitor, $R_m \simeq 10$ GV. For the muon telescope underground at Embudo, $R_m \simeq 100$ GV. Let us concentrate only on the time of maximum of the diurnal variation. It is clear that the diurnal time of maximum (uncorrected for the geomagnetic bending of the primaries) remains nearly constant from 1962 to 1970, at about 15 hours LT. This situation is upset in 1971 when an anomalous shift towards early hours is observed. It appears that this shift has continued at least up to 1976. Such a drastic change was last observed during the deep solar minimum of 1954. The effect remains unexplained. Note however that 1971 was not the year of solar activity minimum.

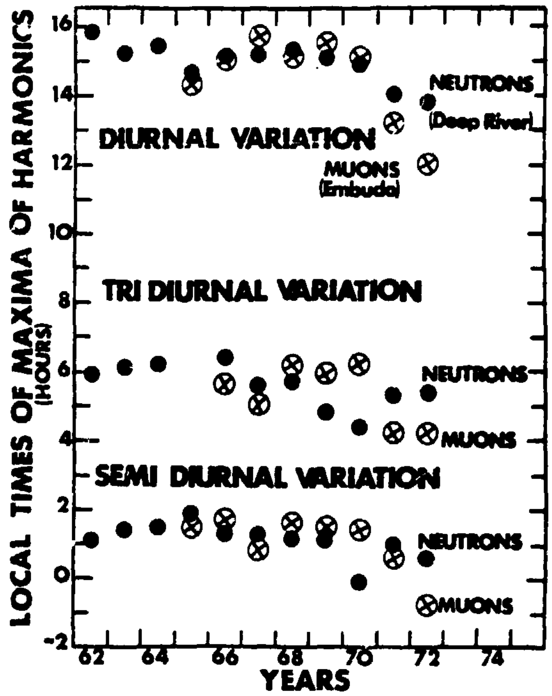

Figure 3

4. Off-Ecliptic Cosmic Ray Contribution to Solar Anisotropy. Figure 4 illustrates one possible way in which our results may be understood. It is known that during 1970-72 period solar wind was undergoing a drastic transition. A pattern of high speed streams, corotating with the sun, was beginning to emerge. They are related to the coronal holes (Krieger et al., 1973a,b). Since the holes often extend over a wide range of helioaltitudes, it follows that on such occasions a large-scale structure of unidirectional magnetic fields must exist in space over a large enough range, normal to the ecliptic plane. A similar inference has been reached independently by

Svalgaard et al. (1974). They studied the long-term changes in the observed solar sector structure pattern of the interplanetary magnetic field. It appears to us therefore that off-ecliptic cosmic rays must make a significant contribution to the cosmic ray solar diurnal anisotropy.

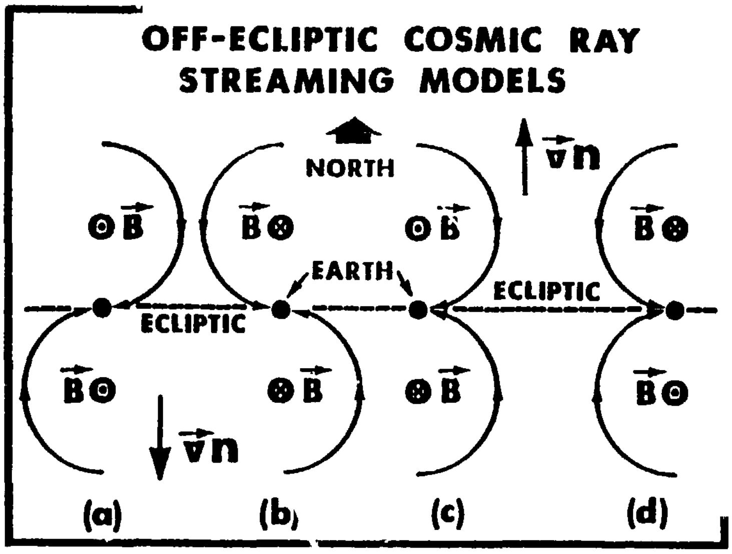

Figure 4

Figure 4 shows the streaming patterns of off-ecliptic cosmic rays under different configurations of the large-scale, well-ordered, interplanetary magnetic field far away from the ecliptic plane. The suggested streaming is driven by a symmetrical cosmic ray particle density gradient ($\vec{\nabla}n$) normal to the ecliptic plane, as shown in the diagram. Off-ecliptic cosmic ray contributions to the solar anisotropy is illustrated in Figure 5. Clearly a great deal of flexibility is available in accommodating departures of amplitudes and times of maximum from those pertaining to the Corotational Anisotropy discussed in section 3. Streaming models 5a,b give rise to semi-diurnal variation of cosmic rays, as discussed by Subramanian and Sarabhai (1967) and Quenby and Lietti (1968). Also the models shown have the potential of explaining the observed features of the day-to-day, as well as year-to-year changes in the solar diurnal variation of cosmic rays. But the most important feature of these models is that one may also be able to derive information regarding the mean interplanetary magnetic field far away from the ecliptic plane, using data obtained with the muon telescopes located deep underground. Moreover one may be able to obtain information regarding the off-ecliptic scattering processes which affect cosmic rays, by comparing data obtained with muon telescopes located underground with data obtained with surface level muon and neutron detectors. Thereby one can get some feel about the "roughness" of the off-ecliptic interplanetary magnetic field. In addition one notes that at very high energies off-ecliptic cosmic rays might carry information about the characteristics of the boundary between the heliomagnetosphere and the interstellar medium. Sp ce at such large distances is unlikely to be sampled in depth by the spacecrafts, at least in the present century.

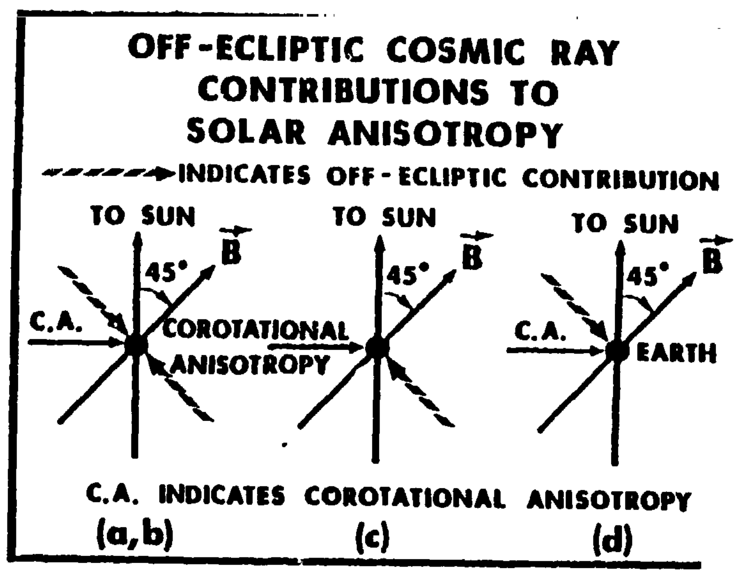

Figure 5

I hope that I have convinced you of the potential usefulness of the cosmic ray technique in acquiring information about the broad features of the interplanetary magnetic field, far away from the ecliptic plane. A very modest investment of funds in keeping alive the remaining relics of the global network of neutron and muon detectors would ensure that vital data of high quality are available to the scientific community for a variety of uses. Also some money should be made available to research workers on a continuing basis, to carry out a variety of analyses of the data to acquire insights which might prove very useful to NASA programs in the future. Such studies would be very useful in the design of experiments to be put aboard the future spacecrafts. Alternately when the measurements do become available from the space probes it might become possible to further refine the theoretical models of the observed modulations of energetic particles. This is, of course, quite vital to the continued good health of the field, as well as to the triumphant march of science itself.

Acknowledgement. This research is supported in part by the National Science Foundation under Grant #ATM78-10727.

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SOLAR CORONAL HOLES AND COSMIC RAY INTENSITY VARIATIONS

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ABSTRACT

A relationship between the (North-South) asymmetry in the areas of the solar polar coronal holes and the (North-South) anisotropy in the cosmic ray intensity has been pointed out by Agrawal et al (1978). However this study was limited to the short interval of skylab observations.

The present study extends the above investigation over a period of two years, using ground-based observations of coronal brightness obtained by the K-Coronameter. It has been pointed out by Hundhausen (1977) and Bohlin (1977) that the low brightness regions in the contour maps of coronal brightness (plotted as a function of solar latitude and Carrington longitude) correspond well to coronal holes observed by other techniques. Periods for study of cosmic ray variations have been chosen maximizing the asymmetry of the polar coronal holes. The study substantiates the general conclusions of the limited study and underscores the importance of the role played by coronal holes in the solar modulation of galactic cosmic rays.

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Introduction:

Systematic studies of cosmic ray intensity variations over the past four decades have highlighted the importance of the use of the same as tools for exploring the interplanetary space. The streaming into the solar system of galactic cosmic rays from beyond and the modulation of the same by the interplanetary electromagentic state, which in turn is governed by the sun, have been generally accepted.

A variety of cosmic ray intensity variations are often sumultaneously present and these arise from different causes. The following modulations and anisotropies can be cited as examples: solar cycle variation, Forbush decrease, specific recurrent decreases, daily variation consisting of first, second and perhaps higher harmonics, (N-S) anisotropy etc. A sorting out of this complex mosaic of intensity changes attributed to different modulation mechanisms is not always an easy task.

While solar activity is still recognized as the primary cause that modulates and governs the interplanetary medium, there has been a resurgence of the search and isolation of appropriate solar parameter(s) for correlative studies with different types of cosmic ray intensity variation.

Role of solar wind in changes of cosmic ray intensity:

It has been recognized that the velocity of the solar wind plays an important role in the development of geomagnetic activity. The correlation between geomagnetic activity and some of the cosmic ray intensity variations is also well known. Thus the question has been raised for quite some time whether solar wind speed also has any bearing on cosmic ray intensity changes. Past studies have often produced conflicting or inconclusive results.

Snyder et al (1963) have reported a negative correlation between daily means of solar wind speed and cosmic ray intensity,but the correlation was not very strong. The study of McCraken et al (1966) of a series of recurrent Forbush decreases, has indicated that these are associated with the emission of high speed solar plasma from the so-called "M-regions" (Bartels, 1934) which are the restricted areas on the solar disc to which recurrent geomagnetic distrubances are attributed. Also, it has been suggested by Haurwitz et al (1965) that the magnitude of the flare-associated Forbush decreases might be proportional to the speed of the flare-plasma cloud, which in turn is related to the field strength ahead of the cloud. The study of Iucci et al (1977 a) supports this general result. It is relevent to point out that the studies of Mathews et al (1977), and Hedgecock et al (1972) have concluded that the long-term (11-year) cosmic ray modulation cannot be explained strictly on the basis of the solar cycle variations in the solar wind speed as observed in the ecliptic plane.

Coronal holes, high speed streams and cosmic ray intensity variation:

It has been realized of late that high speed streams are closely related to coronal holes, and that the equatorial coronal holes are probably the 'M-regions' of Bartels (Vide review, Akasofu, 1976). Interest has again been sparked in the possible relation between coronal holes, solar wind speed and cosmic ray modulation. Decrease in cosmic ray intensity during 1965-1974 have been studied by Iucci et al (1977 b), when the earth was immersed in high speed streams which could be associated with coronal holes. They report increases in high latitude neutron monitors $\sim$ 0.6% for each increase of 100 km/sec in solar wind speed.

Furthermore, various cosmic ray studies suggest that mechanisms operating in the off-the-ecliptic plane could contribute significantly to the intensity changes. Thus the nature of the physical processes in the solar polar regions are of significance. It is not known at present how the solar wind and solar magnetic fields relating to the polar regions of the sun contribute to the modulation of galactic cosmic rays incident upon the solar system from off-the-ecliptic plane regions. Schwenn et al (1978) have pointed out the helio-latitude dependence of solar wind. The investigations of Duggal and Pomerantz (1971,1976) and Mercer et al (1971) refer to cosmic ray modulation in the north and south pointing directions, for interplanetary shock waves propagating at larger angles with respect to the ecliptic plane. The relatively poor correlation between solar wind speed and cosmic ray intensity variation, particularly on a long term basis is to be pointed. This arises partly from the fact that measured solar wind speeds used in analyses have essentially been restricted to the ecliptic plane (± 7.5°).

Furthermore, any attempt to correlate the various types of cosmic ray intensity variations with suitable parameter(s) of solar activity, it is also necessary to sort them out and investigate, whenever possible, the different types, in an isolated fashion.

The study of Agrawal et al (1978) utilizes the published data of the sizes of the solar polar coronal holes from five different intervals of skylab observation during 1973-1974 (Bohlin, 1977) and the (North-South) anisotropy obtained from the cosmic ray intensities registered by the ground level super neutron monitors at Thule and McMurdo Base, Antarctica. Note that no daily variation of cosmic ray intensity is involved in the data. Also, to a certain extent, anyother type of world-wide variation on an average would be removed in the difference except those connected with a (N-S) effect.

Extension of the study of cosmic ray (N-S) anisotropy study using ground-based data relating to polar coronal holes:

Daily values of polarization brightness, observed as a function of latitude at 0.5 solar radii above the west limb of the sun, by the K-Coronameter at the Mauna Loa observatory have been used to generate contour maps of coronal brightness as a function of solar latitude and Carrington longitude (of the limb at the time of observation). Such contour maps of "white light" are available for long periods of time. For the Skylab epoch itself, the low brightness regions in such maps correspond well to coronal holes observed by other techniques. Thus in principle, we have a means of extending studies involving polar coronal holes over long periods, using the relatively readily available ground based data.

The present study deals with the two year period 1973-1974, an interval characterized by several features of interest. Solar activity in terms of sunspot numbers is at the lowest part of the descending phase of the sunspot cycle prior to the minimum. The period 1973-1975 has revealed a high degree of correlation between the occurrence of coronal holes, solar wind streams and geomagnetic disturbances as pointed out by Neupert and Pizzo (1974), Nolte et al (1976 a,b), Sheeley et al (1976), and Bell and Noci (1976). This would refer to the presence of low latitude coronal holes. It is relevent to draw attention to the close association between high speed solar wind streams and solar coronal hole structures, as pointed out by Bohlin (1977), Hundhausen (1977), and Sheeley and Harvey (1978).

The present study is devoted to investigate the cosmic ray (N-S) anisotropy that is possibly associated with the equatorial extension of magnetic fields from solar polar coronal holes. The cosmic ray data refer to the intensity measured by the detectors at the two polar stations of McMurdo and

Thule. The choice of intervals for study during this period 1973-1974 is made with care and according to specific criteria. The intervals should consist of not less than four successive days. The absence of solar flare within two days on either side of the interval is a pre-requisite for the choice of the interval of study. The (N-S) coronal hole area asymmetry is maximized by the choice that the polar hole almost extends equatorward for one hemisphere and in the other hemisphere extends only up to $\sim 45°$ latitude. Care is also taken to see that the interplanetary magnetic field is of singular sign during this entire interval. Thus the restrictions introduced with regard to the selection of the interval for study enables us to remove to a large extent cosmic ray intensity variations arising from other possible causes and thus isolate the effect of the (N-S) asymmetry of the areas of polar coronal holes on the cosmic ray anisotropy. The results in general substantiate the earlier results of Agrawal et al (1978) which had been obtained over a limited period of study. It is seen that if the dominant hole is in the northern hemisphere, the (N-S) anisotropy in cosmic ray intensity is negative, and positive for the cases of dominant southern hemisphere hole.

Conclusions:

The following conclusions emerge from the study:

1. Solar coronal holes play a significant role in the modulation of cosmic ray intensity variations.

2. The North-South (N-S) cosmic ray anisotropy as measured at 1 AU during non-disturbed periods is dependent on the difference in areas of the solar polar coronal holes, when such values were specifically available for study, as during the skylab period.

3. It is now possible to extend this study over long-term periods

by using the ground based observations of the K-Coronal whitelight, since regions of weak emission of the K-Coronal whitelight have been found to correspond well to coronal holes observed by other techniques. The study extended to a period of two years, generally supports results of the earlier short term study.

4. Thus it is clearly seen that mechanisms operating in off-the-ecliptic plane contribute significantly to the cosmic ray intensity changes.

A detailed correlative study of the asymmetry of coronal hole areas, recognized from complementary K-Coronal data and the cosmic ray (N-S) anisotropy, obtained from the difference in intensity registered by the Thule and McMurdo neutron monitors over the period 1973-1974 is being reported elsewhere (Manuscript under preparation).

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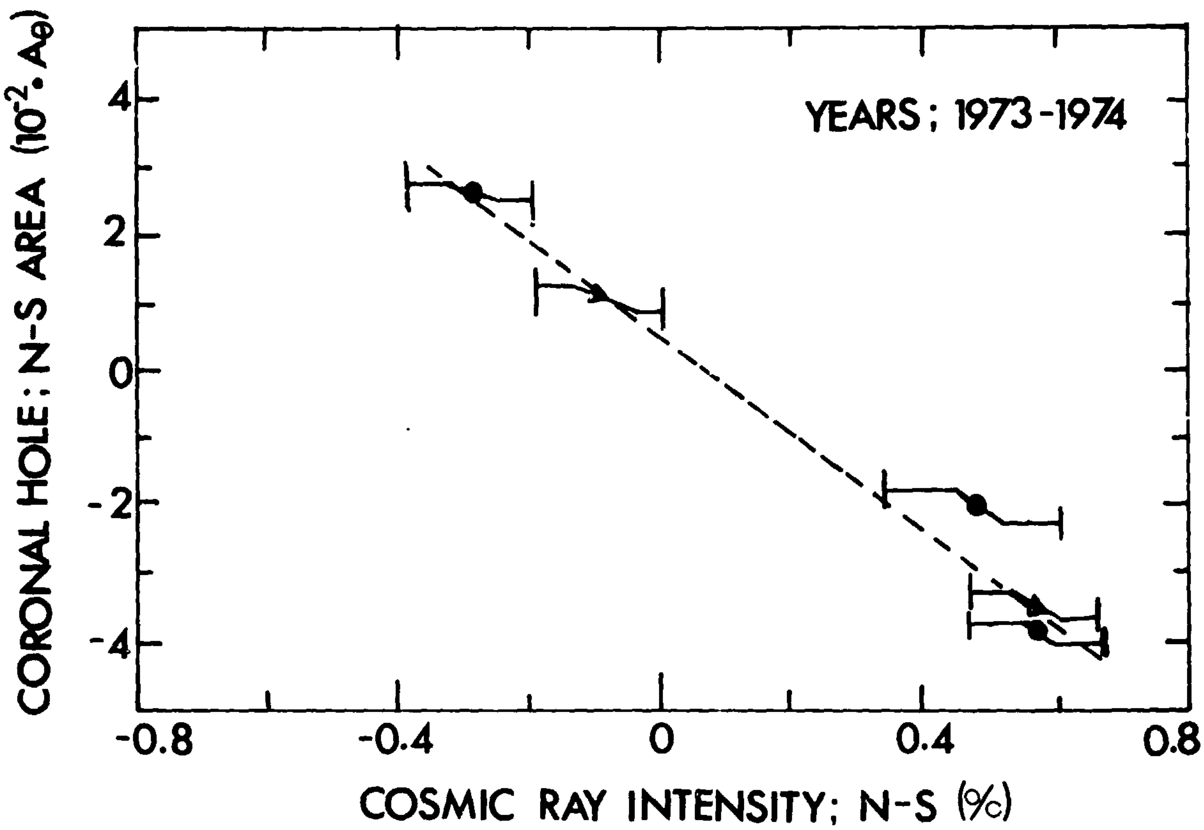

Figure 1

Crossplot of (North-South) asymmetry in the sol -olar coronal hole area versus the (North-South) anisotropy in cosi -ay intensity derived from the Thule and McMurdo neutron monitors. Both observations of data correspond to the same period in the interval 1973-74 of the Skylab observations. The cosmic ray data has been corrected for latitudinal position of earth in terms of ecliptic plane (for details, see Agrawal et al (1978)). $A_{\odot}$ = Area of the visible solar disc.

ΘN/ ND

SOLAR ACTIVITY AND TERRESTRIAL WEATHER: THE MAGNETIC COUPLING MODEL

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Both short term (day-week) and long term (decade-century) correlations between solar activity and various perturbations of the weather have been convincingly demonstrated by the work of Eddy[1], Roberts[2], Stringfellow[3], Wilcox et al[4]. In essence: (1) short term fluctuations in atmospheric vorticity in the winter have shown high correlation (7 sigma) with interplanetary magnetic field (IMF) sector polarity changes (which, in turn, are highly correlated with geomagnetic disturbances); (2) periods of harsh winters have been shown to correlate with low solar activity (i.e., low numbers of sun spots, geomagnetic storms, auroras, etc.); and (3) lightning incidence, over four solar cycles, exhibited a strong 11 year and a distinct 22 year modulation. These effects are predicted by the magnetic coupling model most of whose features have been observed. The causal chain for (1) and (2) above is: IMF modulation of cosmic rays producing changes of approximately 15%[5] in atmospheric ionization at 10 km altitude (approximately 250 grams/cm depth) resulting in variation of mid-to high-latitude cirrus cloud cover by the mechanism discussed below. Although the variation in ionization increases with altitude, the mixing ratio becomes rapidly too small for cloud formation above the cirrus region. Because loss of heat through a cloudless sky is the major factor in determing winter severity, variation in cloud cover explains the strong correlations holding in winter only. The 11 year synchronism of lightning incidence with the sun-spot cycle has been adequately explained[11] as due to leakage of charge from anvil to electrosphere when cosmic ray ionization is high. We explain the 22 year modulation of lightning in another account (see below).

The principal cosmic ray variations of interest here are (1) the well-known "11 year solar cycle" modulation which anti-correlates with sun spot number, (2) the Forbush decreases due to large magnetic structures enveloping the earth for days at a time, more often near solar maximum, and (3) the strongly geomagnetic latitude dependent north-south-asymmetry (NSA) due to day side merging between the IMF and GMF (geomagnetic field). The latter effect combined with the $\pm 7^{\circ}$ heliocentric latitude excursions of the earth[6] produces 22 year cycles. This NSA has been observed with (1) 2000% amplitude at low energy[7,8] (Mev), (2) 30% amplitude in the 1 Gev/nucleon range[9], and (3) 1% in neutron monitor records[10] (10 Gev). A more extensive discussion of these phenomena appears in a much longer paper currently in preparation for submission to Science.

The reduction in cirrus clouds postulated in this model to result from increased atmospheric ionization involves several factors: (1) the coalescing water molecular aggregate is an excellent inelastic collector of charge[12] before it has cooled to an ice-crystal or grown large enough to reflect IR,

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(2) charged water molecular aggregates are transported up or down (out of the thin cirrus region) by the atmospheric electric field (5 v./meter at 10 km), and (3) the region in which cirrus ice crystals can form is quite thin (because the temperature must be below -40°C if no condensation nuclei are present, and, the mixing ratio falls off very rapidly with altitude (usually)).

On the basis of this model, it would seem that our understanding (and possible future predictive power) of the solar activity perturbations of weather would be enhanced by measurements that (1) permit analysis of the solar dynamo source of the IMF, and (2) clearly define the influence of the IMF on galactic cosmic rays (and thereby on cirrus level ionization and related effects). This work was performed under ONR Contract N00014-77-C-0392.

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ABSTRACTS FROM AMERICAN
ASTRONOMICAL (AAS) BULLETIN
APPENDIX B

SPECIAL SESSION OF SOLAR PHYSICS DIVISION OF AMERICAN ASTRONOMICAL SOCIETY

Solar and Stellar Variability

GEORGE ELLERY HALE AND ACTIVE MAGNETIC FIELDS

E.N. Parker

George Ellery Hale invented the spectroheliograph to study the activity of the sun and then established from the Zeeman splitting of a number of lines in sunspot umbrae that strong magnetic fields are an intrinsic part of the sunspot. These pioneering observations, and the spectroheliograph and magnetograph in their various modern forms, are the basis for modern studies of the magnetic activity of the sun and of stars and galaxies. Mos stronomical bodies have magnetic fields and, hence, are active. The theoretical understanding of magnetic fields embedded in highly conducting gases has progressed over the decades but is still without solid explanations for much of the activity. Observation continues to lead the way, continually turning up new effects that not only were not anticipated but have yet to be understood after the fact. The turbulent diffusion of magnetic fields is, after three decades of theoretical controversy, well established as a real effect in nature, but with the surprising associated effect of negative diffusion in suitably long lived eddies. The behavior of magnetic fields in a convective stellar envelope, then, is complicated by the buoyancy of the field, by convective propulsion, and by turbulent diffusion. Together these effects guarantee that the magnetic fields within the envelope are delivered to the surface where the intrinsic internal nonequilibrium of magnetic fields produces the extensive array of suprathermal effects collectively called activity. For all the wide occurrence of magnetic activity in the Universe, the sun and the magnetosphere of Earth are the two places where the physics of the activity can be observed in enough detail to progress toward understanding the physics. The primary cause of magnetic activity is the nonequilibrium that results when any flux tube extends from one pattern of winding about its neighbors into another. For in that circumstance there is at least one thin layer from which the fluid is squeezed so that the gradient of the magnetic field increases without bound, until resistive diffusion steps in and dissipates the field. The sunspot, and its magnetic field discovered by Hale, is a particularly vexing phenomenon, having resisted any overall self-consistent explanation up to the present time. We have suggested that the sunspot is merely the magnetic debris on the surface of the sun marking the position over an unseen subsurface downdraft. No other concept seems to account for the spontaneous clustering of so many separate individual flux tubes into a single bundle. As a final point, the observed strong variation of the mean level of solar activity over the centuries is presumed to be a consequence of changes in the internal convection and circulation beneath the visible surface of the sun. Hence we would expect at least some slight change in the total luminosity of the sun in step with the changing level of activity. This entire question is of fundamental importance to the physics of stellar interiors and stellar activity, besides being of profound consequence to the correlated variations of the climate of Earth. Hence, precise measurements of the absolute intensity of the sun, to absolute accuracies of at least one part in 10^3, must be begun now and extended indefinitely into the future, as the only direct means for studying the problem (measurements by Kosters and Murcray suggest variations of as much as 0.4% over the last ten years). The relative luminosities of a number of the nearer main sequence G-stars should be measured to supplement the direct observations of the sun, showing by the changes in each of many stars, the possible variations of the sun over long periods of time.

SOLAR LUMINOSITY VARIATION: OBSERVATIONAL EVIDENCE AND BASIC MECHANISMS

P.V. Foukal

We review the evidence on variations of the total solar luminosity, with particular attention to the results on changes over time scales between days and tens of years. We summarize the time behavior of the solar constant and of the solar spectral irradiance for comparison with observations of other late-type stars, and also for its possible significance as an input to climate models. We discuss some physical process that might give rise to variation of the

total luminosity in the shorter time scales, and point out how the observable parameters of solar luminosity variation can provide a useful technique to study the dynamics of gas and magnetic fields in the convection zone. We suggest some useful observations to be made from the ground and from space in the future.

OPTICAL VARIABILITY OF LATE-TYPE DWARFS AND RS CVn STARS; EVIDENCE FOR LUMINOSITY CHANGES AND SEARCHES FOR SUN SPOT CYCLES

L. Hartmann

The observational evidence for luminosity variations that may be related to solar-type activity on other stars is reviewed. Spots have been identified on late-type stars, based on the demonstration of inhomogeneous surface brightnesses derived from eclipses of binaries, and on the general lack of alternatives with appropriate period, light-curve, and color behavior.

Modern photoelectric determinations of spot properties appear to favor spot temperatures a few hundred degrees cooler than the surrounding photosphere, but the results are not unique, and bright spots may also be present. Suggestions that spots may trace out differential rotation have come from the observed migration of the light curve with respect to the eclipses in RS CVn stars, and from period changes in dwarfs; however, it is not clear whether the period changes reflect differential rotation or spot evolution.

Spot variability may occur on timescales of days. However, photographic studies with a time baseline ~ 60 years, completed for four dwarfs, show long-term drifts in optical light on the order of 30%, with timescales of decades. No real evidence for 11 year cycles has been found, in contrast to Wilson's Ca II emission observations, but this discrepancy may be due to the limited accuracy of photographic plates. Similar kinds of behavior are present in RS CVn stars; spot areas may persist for periods up to decades.

Standard spot models translate the 30% optical variability into ~ 10% luminosity variations: this should be confirmed by bolometric observations. The available long-term studies and statistical arguments suggest that variability may be intermittent. The long timescales present in the observations indicates that suppression or modification of convection in the outer envelope persists for timescales longer than the overturning time.

THE VARIABILITY OF THE SOLAR ULTRAVIOLET RADIATION IN THE WAVELENGTH REGION 1200 - 2100 Å

M.E. Vanhoosier, J.W. Cook, and G.E. Brueckner

The intensity contrast I(plage)/I(quiet Sun) has been determined for continua and selected strong emission lines between 1200 Å and 2100 Å, using spectra obtained from Skylab and from sounding rockets. We find values of 10 (1400 Å), 4 (1600 Å), 2 (1800 Å), and 1 (2100 Å) for the ultraviolet continuum. The contrast for H Ly-α is 3.5. A minimum value for the solar variability has been derived under three assumptions: (a) the enhanced UV radiation originates from the same plage areas as observed in Ca II K_2 images, (b) our contrast values are typical, (c) average quiet and plage intensities per unit surface area are constant over the solar cycle. A high spatial resolution photograph of a plage obtained from a sounding rocket on 13 February 1978 supports assumption (a) for the 1600 Å continuum. Approximately 20% of the flat disk area was covered by plage at the solar maximum of 1958 according to Sheeley (Ap. J., 147, 1106), while the sunspot number reached a monthly average value in excess of 200. For such a strong solar cycle the ratio of full disk flux at solar maximum to that at solar minimum will be 1 (cont. at 2100 Å), 1.20 (cont. at 1800 Å), 1.60 (cont. at 1600 Å), 2.80 (cont. at 1400 Å), and 1.50 (H Ly-α).

VARIATIONS IN THE SOLAR BRIGHTNESS DUE TO ACTIVE REGIONS

G.A. Chapman

Observations of faculae and sunspots obtained with the Extreme Limb Photometer (Chapman, G. A., Phys. Rev. Lett 34, 755, 1975) are presented as fractional changes in the mean solar brightness. These observations were obtained at $\lambda = 0.52\ \mu m$ with a bandpass of $\Delta\lambda = 0.07\ \mu m$. Observations were obtained in 1974 and 1975 of sunspots near disk center and faculae near the limb. Estimates of the brightness deficit of sunspots are often made from their area and assumed contrast. Such estimates may be substantially in error preventing accurate comparisons with other forms of synoptic total disk brightness monitors. For example the estimated effect of Mt. Wilson sunspot No. 19448 (9 Aug. 74) gave a fractional decrease in solar brightness, $\Delta B/B \approx -1 \times 10^{-4}$ whereas the photometric value was -2.1×10^{-4}. Neglecting the facular areas, 4 or 5 large sunspots groups could give $\Delta B/B \approx -1 \times 10^{-3}$. We find for sunspots the relation $\Delta B/B \approx -6.3 \times 10^{-1}$ A, where A is the S.G.D. area in fractions of a hemisphere. For faculae about 6" - 30" from the limb we find $\Delta B/B \approx (13 \pm 1) \times 10^{-3}$ A, where A is the McMath area in fractions of a hemisphere. Bolometric variations should be about 15% less than the values given above.

THE EXTREME-ULTRAVIOLET SOLAR CYCLE

J.G. Timothy

There is evidence for a large variability in the solar extreme-ultraviolet irradiance over the solar cycle. The magnitude of the variability as a function of wavelength and its relationship to the dynamics of the outer solar atmosphere have yet to be determined. We are initiating a series of measurements to address these questions and will discuss their relevance to SCADM.

TOTAL SOLAR ENERGY OUTPUT AND ITS MEASUREMENT

V. Domingo

The expectations and the indications of total solar energy output variation are analysed on the bases of solar physics theory, solar activity observations and climatological observations. Our present effort to measure the total solar energy output (solar constant) is described and how the present techniques can be improved to be able to measure the expected variations of the solar radiation, is discussed.

ULTRAVIOLET OBSERVATIONS OF HZ-HERCULIS

H. Gursky, A.K. Dupree, L.W. Hartmann,
J. Raymond, R.J. Davis, and J. Black

We have carried out extensive observations of HZ Herculis with IUE. Data has been obtained at all orbital phases but only within several days of the x-ray turn-on that defines the 35-day cycle. Intensity variations appear to be similar to those observed in visible light. The bulk of the continuum radiation can be accounted for by radiation from an x-ray heated photosphere. Excess radiation can be interpreted as originating in an accretion disc for which we can define certain physical parameters. Only emission lines are seen in the spectrum; NV is the strongest spectral line and the ratio of NV to CIV display significant variations with orbital phase.

GAS STREAM OBSERVED IN THE ULTRAVIOLET SPECTRUM OF U CEPHEI

Y. Kondo, R.E. Stencel and G.E. McCluskey

The interacting close binary U Cephei has been observed with the International Ultraviolet Explorer. Nine high resolution spectra in the mid-ultraviolet (1900 - 3200A) and one high resolution spectrum in the far-ultraviolet (1200 - 1900A) were obtained. The effect of gas streaming are clearly seen in the mid-ultraviolet resonance lines of Fe II (λ2599) and Mg II ($\lambda\lambda$2795 and 2802), all of which are markedly phase-dependent. The data indicate that much of the gas leaving the G star circles behind the B star and leaves the system. It is suggested that g-mode oscillations in the G star supply part of the energy required to drive the gas out of the system.

SECULAR DECREASE IN THE SOLAR DIAMETER, 1863-1953

J.A. Eddy and A.A. Boornazian

Meridian transit measurements of the solar diameter made at Greenwich from 1836 through 1953 show a statistically significant secular decrease that exceeds errors of observation and likely observer bias. The same secular effect has been noted before by others who examined all or part of the Greenwich data set, and has generally been attributed to atmospheric effects or personal equation. It does not appear in the less precise measures of $D_\odot$ made at Campidoglio and Monte Mario from 1874-1937. We are now analyzing the series of transit measurements made at Washington beginning in 1846 as another check. The Greenwich decrease is a nearly monotonic feature of both horizontal and vertical diameters: a least-squares fit gives 2.25"arc/century in D_H and 0.75"arc/century in D_V. If this measures a real change in the solar diameter it amounts to about 0.1%/century, which is far more than the rate proposed by Helmholtz in 1854 to explain the solar luminosity. If it indicates a temporal contraction of the photosphere it could contribute an adequate fraction of $L_\odot$ to reduce the theoretical internal temperature and expected neutrino flux.

VARIATIONS OF THE SUN'S RADIUS AND TEMPERATURE DUE TO MAGNETIC BUOYANCY

J.H. Thomas

Recent measurements have suggested that the sun's surface temperature decreases with increasing solar activity (Livingston 1978, Nature 272, 340). Although this has been interpreted as implying a decrease in luminosity, it is pointed out here that surface cooling could also be due to a radial expansion of the sun with no change in luminosity. The proposed physical mechanism for the expansion is based on variations in magnetic buoyancy due to variations in the magnetic flux in the convection zone over the solar cycle. Rough calculations show that this mechanism could cause a relative change of solar radius $\Delta R/R \sim 10^{-4} - 10^{-3}$ between solar minimum and maximum, with a corresponding drop in surface temperature of $\sim 1 - 10$ K. Past measurements of variations of the sun's radius over the solar cycle are inconsistent, but there are data in support of the present hypothesis. Accurate monitoring of the sun's radius over the solar cycle would test this hypothesis and provide new information on the mechanism of the solar dynamo. This research was supported by NASA and the Air Force Geophysics Laboratory.

LARGE VELOCITY SHIFTS IN SHARP UV RESONANCE FEATURES IN SPECTRA OF EARLY-TYPE BINARIES

F.C. Bruhweiler, Y. Kondo and G. McCluskey

In 19 early-type binaries studied using the IUE spectrometer, 5 objects (βLyr, ηOri, AOCas, HD93403, and μSgr) display sharp features of SiIV and CIV (and NV in βLyr) with large velocity shifts in excess of 85kms^{-1}. In βLyr and μSgr, multiple exposures reveal that narrow absorption features of these ions are clearly variable and appear linked with the phases of the binary systems. In η Ori, with one exposure available, lines of the CIV resonance doublet near 1550A are shifted approximately 75A shortward from the rest wavelengths. In AO Cas, multiple exposures show components presumably of interstellar origin of SiIV and CIV with additional narrow circumstellar shell components shifted shortward by 1800kms^{-1}. A single IUE spectrum of HD93403 shows a SiIV component at 1402.6A, presumably interstellar plus an additional component shifted longward by 85-130kms^{-1}. Since all these objects are early-type binaries, these observations are not inconsistent with explanations involving mass loss or mass exchange. But due to the high frequency of binaries and the high occurrence in the stars observed in this study of both negative and positive velocity absorption components, large contributions in interstellar features from circumstellar material or from a mass stream between stars with unresolved velocity shifts must be seriously considered. Since the velocity resolution of IUE is on the order of 30-40kms^{-1}, difficulties may arise in obtaining an unambiguous interpretation for the origin of narrow instellar features of high ionized species observed along any line of sight.

IUE ULTRAVIOLET SPECTRA OF CLASSICAL CEPHEIDS

S.B. Parsons

The classical cepheid variables δ Cep (5.37 days) and β Dor (9.84 days) were observed with IUE in December 1978 at several phases each, especially in the interval 0.7 - 1.0 P. Two phases (.76 and .86 P) were observed of ζ Gem (10.15 days). Most sets of observations cover the full range 1200-3300 Å available at low resolution (6 Å) and usually the range 2400-3200 Å at high resolution (≈0.3 Å) Similar spectra were obtained of non-pulsating supergiants over the spectral type range FO Ib - G2 Ib. Very little if any flux is recorded shortward of the Si I opacity edge near 1680 Å, although O I λ1304 emission appears at type F8 Ib and is very strong at G2 Ib, along with Si II λ1814 emission. O I emission and Mg II emission cores are present at all observed phases of β Dor but at no observed phases of δ Cep. From this it is speculated that the presence of a substantial chromosphere is related to the small difference in mean temperature of the cepheids (δ Cep averages about 250 K hotter) rather than to the actual large changes in temperature or specific hydrodynamic events during their pulsations. No explanation is evident yet from the spectral data for the bumps on the λ1910 light curve of β Dor observed by OAO-2 filter photometry (Hutchinson, Hill, and Lillie 1975, A.J. 80, 1044). Further study of line identifications and flux distributions is in progress. I gratefully acknowledge the assistance of the IUE Observatory staff in the acquisition and reduction of these data. This work is supported in part by NASA under grant NSG 5328.

PERIOD CHANGES OF WUMa SYSTEMS

T. Herczeg

A comprehensive study of period changes in WUMa-type eclipsing binaries is being carried out, based on the available observational material and several new photoelectric timings of the minima. About 35 systems lend themselves to a detailed analysis of the period. It is quite clear that the period changes consist almost exclusively of abrupt, discontinuous variations with the period being constant or nearly constant between them. The "sudden" changes need typically 5-10 months to lead to a new value of the period, but they can be as short as a few weeks, in extreme cases possibly only a few days. Intervals of constant period between discontinuities vary between 5 and 35 years and the abrupt changes appear to be distributed randomly. Amounts of typical period variations lie between 0.1 and 0.5 sec with a peak around 0.3 sec; there seems to be a tendency that positive changes predominate by about 2:1 above negative changes, but the significance of this finding can not be definitively established without further observations. Accepting this as representing a secular trend would lead to substantial changes in these systems within 5 to 10 million years--a time scale probably too short. This work is supported in part by NSF grant AST 78-12307.

THEORETICAL COLORS FOR HELIUM RICH CEPHEIDS

R.W. Whitaker and R.L. Kurucz, et. al.

The authors have suggested that certain cepheids may have solar like winds which deplete their atmospheres of hydrogen. The helium enrichment can explain the mass discrepancy for these stars. We have computed UBV and ubvy colors for a modest grid ($1.0 \leq \log(g) \leq 3.0$; $5500°K \leq T_{eff} \leq 7000°K$) of stellar atmospheres with $Y = 0.27$ and $Y = 0.75$. The latter value is an upper limit for helium enrichment suggest by Cox et. al. New ODFs for $Y = 0.75$ have been computed and used in Kurucz's ODF version of the ATLAS stellar atmospheres computer code. Our results are compared with those of Sonneborn et. al. (1979, submitted Ap. J.).

ROTATION BROADENING FUNCTIONS OF SELECTED W URSAE MAJORIS STARS

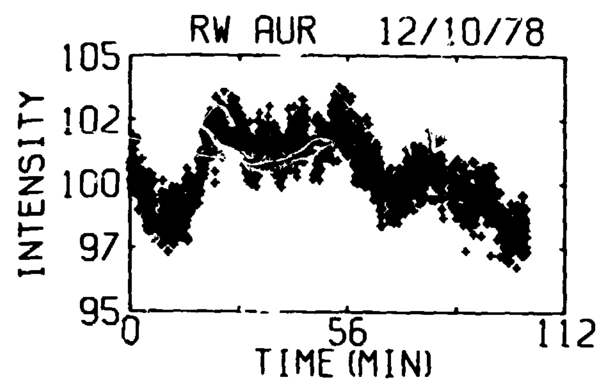
L. Anderson, M. Raff and F.H. Shu

Through the technique of Fourier deconvolution we have been able to extract rotation broadening functions from the spectra of several W UMa stars. If one assumes that each surface element on a star emits radiation with the same spectral distribution but not necessarily the same integrated intensity as the next element (the "uniform profile approximation"), then the spectral distribution received at Earth is a frequency convolution of the appropriately Doppler shifted intensity distribution over the visible surface of the star (Shajn and Struve 1929, M.N., 89, 222). We digitize and take the Fourier transforms of photographic spectra covering some 500 Ångstroms and including several dozen strong lines, and deconvolve with equivalent spectra from non-rotating single stars of similar spectral type (Simkin 1974, Astr. and Ap., 31, 129). The resulting rotation broadening functions contain information on the shape (e.g., degree of contact and mass ratio) not easily obtained from light curves or the analysis of individual strongly blended spectral lines.

SHORT TIME SCALE BRIGHTNESS FLUCTUATIONS IN T TAURI STARS

T.J. Scneeberger *, S.P. Worden and J.L. Africano

We have conducted an investigation of short period brightness fluctuations in the T Tauri stars at the Cloudcroft Observatory. The 1.2 m f/6.5 telescope equipped with a single channel pulse counting photometer has been used in a high speed mode consisting of sequential 5 sec integrations in the U band for durations up to two hours. The figure below shows an observation of RW Aur, the most active star observed. Comparison stars were constant to ±0.01 mag. This star also has times of relative quiescense. We find a strong resemblance between an event observed on RW Aur and a "slow" flare on YZ Cmi. The short time scale events observed in a number of stars typically have amplitudes of 5% and durations of 10 minutes.



* NAS/NRC Resident Research Associate

LMC CEPHEIDS WITH PERIODS UNDER 1 DAY

L. Connolly

Photoelectric observations at CTIO have been made of 8 Cepheid-like variables in the LMC. With one exception these variables have been previously classified as Galactic foreground RR Lyrae. The light curves are normal for

Cepheids and they are located in the LMC Cepheid instability strip. But periods for these variables have been confirmed to be all under one day. A unique P-L relation for these variables is apparent from the observations and does not follow the relation for normal Cepheids. Whether these variables are actually Cepheids will be discussed.

NEW PHOTOMETRIC OBSERVATIONS OF V382 CYGNI

R.H. Bloomer, E.W. Burke, C. King and R.L. Millis

The massive 07-type eclipsing binary V382 Cygni has been observed to provide new times of minima for a period study and to provide a light curve for analysis. With eighteen new times of minima and all times available from the literature, a weighted linear least squares calculation results in the light elements:

$$\text{Min I} = \text{Hel J. D. } 2442940.8071 + 1\overset{d}{.}8855143.E.$$

$$\pm 0.0002 \quad \pm 0\overset{d}{.}0000002$$

No secular change in the period is apparent over the last three decades. The V light curve of 453 new observations indicates that the maxima are of equal brightness but that the depth of secondary eclipse varies by about $0\overset{m}{.}03$. The solution to the light curve using the Wilson and Devinney (1971) model indicates an inclination near 87°; therefore, using the radial velocity data of Popper (1978) the stars have masses of $M_1 = 26.7M_{\odot}$. and $M_2 = 18.9M_{\odot}$.

Popper, D.M., Ap. J. (Letters), 220, L11.
Wilson, R.E. & Devinney, E.J., Ap. J., 166, 605

NEAR INFRARED PHOTOGRAPHIC SKY SURVEY IV. THE RECENT APPEARANCE OF NGC 2261

C.L. Imhoff and E.R. Craine

We present a series of 17 photographs of NGC 2261 (Hubble's variable nebula; R Mon) in the yellow and near infrared. These photographs were obtained over a period of a year, included in the same field as the NIPSS calibration cluster NGC 2264. The variability, structure and color differences of the nebula are discussed. Our photographs are compared with earlier photographic material, including the series taken by Lampland, as published by Duncan (1956, P.A.S.P. 68, 517). We note that some of the changes in the nebula occur on time scales of as little as two weeks. This study of an extended object is one of several uses to which the NIPSS photographs may be applied; other aspects are discussed in three poster sessions presented at this meeting.

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SYMPOSIUM ON THE STUDY OF THE SOLAR CYCLE

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